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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

REPORT No: CHEM.502

RAIN EROSION OF MATERIALS
WITH SPECIAL REFERENCE TO RADOMES:

REPORT ON A SYMPOSIUM

HELD AT THE R.A.E. on 6th JUNE, 1955

by

A.A. FYALL and R.N.C. STRAIN

OCTOBER, 1955

MINISTRY   OF   SUPPLY

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ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Rain Erosion of Materials with special reference to Radomes.

Report on a Symposium held at the R.A.E. on 6th June, 1955

by

A. A. Fyall and R. N. C. Strain

R.A.E. Ref. Chem.C.91/848/RNCS

SUMMARY

This report records the proceedings of a symposium held at the Royal Aircraft Establishment to provide a comprehensive survey of the rain erosion of materials in high speed flight.

The report comprises papers covering meteorological aspects, flight and simulated tests, electrical requirements, fabrication techniques, application of protective systems and experimental results on specific materials.

A verbatim report of the open discussions which followed each paper is included.

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1   INTRODUCTION

        With current high speed aircraft the severity of erosion by rain of
forward-facing non-metallic materials has become a serious problem.   A few
minutes at 400 m.p.h. in slight rain (say 0.2 in./h) can cause dangerous
structural damage to a glass fibre/resin nose radome.

        Protective finishes and techniques have been developed to minimise the
damage but because of the lack of critical information on many aspects of
the problem, both theoretical and practical, it was agreed that a symposium
covering a wide range of topics would be beneficial to all concerned with
this problem.   To facilitate a full discussion of all known problems,
arrangements were made for the presentation of classified military
information.

        Representatives of Industry and the Services concerned with rain
erosion attended the Symposium, the number being limited only by the
seating capacity of the R.A.E. Main Conference Room.   Dr. F. E. Jones
DDRAE(E) opened the meeting and Dr. N. J. L. Megson, Head of Chemistry
Department, R.A.E. acted as Chairman during the proceedings.

        Papers covering many aspects of rain erosion were presented and
these papers, together with the discussions which followed, form the basis
of this report.   Some authors found that they had insufficient time to
present the whole of their papers and these omissions have been included.
References are given separately at the end of each paper.

        During the lunch interval the R.A.E. whirling arm test rig, which is
described in Section 5, was demonstrated at 500 m.p.h. and 1 inch per hour
rain.

2   INTRODUCTORY REMARKS BY DR. F. E. JONES DDRAE(E)

        Problems of rain erosion in flight are looming so great at the
present time that they are becoming the holding items on a number of
developments on the Military side.   These problems arise mainly due to
gaps in our basic knowledge of the mechanism of rain erosion and our
comparative lack of knowledge of materials likely to prove useful in
standing up to the impact of rain under the various flight conditions.

        We are hoping that as a result of the papers and ensuing discussions
which make up this Symposium we shall get a clearer picture of the state
of our present knowledge, the problems most urgently before us in the
future and some ideas on how best these problems might be solved.

        I suppose the item of most immediate interest is the radome and I
would say that we have hardly touched on this as far as high speed air-
craft flight or guided weapons are concerned.   Sometime during the day
we shall be hearing of problems of designing radomes for supersonic flight
conditions and there is little doubt, even from the scanty evidence now
available, that the discovery of radar and infra-red transparent materials
which will withstand both rain impact and high temperature is a necessity
for future progress.

3   METEOROLOGICAL ASPECTS OF RAIN EROSION CONTRIBUTED BY METEOROLOGICAL
     OFFICE, AIR MINISTRY AND PRESENTED BY MR. R. J. MURGATROYD,
     METEOROLOGICAL RESEARCH FLIGHT, R.A.E.

     General Remarks

        It should be emphasised at the outset that data regarding drop-size
distribution in rain are extremely scanty and are at present entirely

derived from observations made on the ground. Observations have been made using various techniques at a few places in England and, among other countries, in Canada and America, but all the observations are laborious to make and this has limited the data. In England the observations have been made by exposing a filter paper dusted with Rhodamine-G dye to rainfall for a sufficient time to enable a reasonable number of drops to be caught. The size of the stain on the paper caused by a single drop can be used as a measure of its size. Obviously the time of exposure depends on the rate of rainfall and in the heavy rain associated with thundery conditions, may only be a few seconds. From laboratory experiments the terminal velocities of rain drops as a function of their size has been measured, and by using these values it is possible to obtain the volume distribution of raindrops from the measured distribution received on the ground. Although other techniques have also been used for measuring drop-size distribution on the ground there has, as yet, been devised no satisfactory method of measuring these distributions in the free air. Some qualitative assessment of the way these distributions may vary with height can be made from theoretical considerations and from experience of the distribution of echo intensity in the vertical of the radar echoes from precipitation, using radar operating on wavelengths of 3 cm or 10 cm.

In the sections which follow an attempt has been made to answer the specific questions put to the Meteorological Office. The answers will be given with an apparent precision which the operational data available do not warrant, and it should be borne in mind that the figures quoted are subject to a large degree of uncertainty which, however, is unlikely to be resolved in the near future.

Sub-division of rates of rainfall and proposed names for each category

The following sub-divisions in rates of rainfall were suggested to the Meteorological Office with a request for proposals for a suitable nomenclature.

Range No.	Rate of Rainfall (in./h)
1	0 - 0.1
2	0.1 - 0.5
3	0.5 - 1.0
4	1.0 - 2.0
5	> 2.0

Continuous rainfall (lasting, for example, for an hour or more) at rates greater than 0.5 in./h, or even as high as 0.5 in./h, is rare in temperate climates, and the higher rates are likely only to be encountered in showery and thunderstorm conditions. Rates of continuous rainfall greater than about 0.15 in./h are classified as "heavy" in temperate climates so that it is clear that the nomenclature used for continuous rains is inappropriate to the ranges quoted above. These ranges are however not greatly different from those used in classifying shower intensities up to 2.0 in./h, and using these classifications we have:

Range No.	Rate of Rainfall (in./h)	Classification
1	0 - 0.1	Slight
2	0.1 - 0.5	Moderate
3	0.5 - 1.0	Heavy
4	1.0 - 2.0	Violent

A further category of "torrential" is suggested for Range No. 5 for rates of rainfall greater than 2.0 in./h.

Median volume diameter of raindrops normally encountered in
various ranges

Best[2] has discussed the drop-size distribution in rain as measured on
the ground at various localities and obtained the following empirical
formulae:

$$1 - F = \exp\left[-\left(\frac{x}{a}\right)^n\right] \qquad (1)$$

$$a = AR^p \qquad (2)$$

when F is the fraction of liquid water in the air comprised of drops
having a diameter less than x and R is the rate of rainfall. A, p, n
are empirical constants.

From (1) we have

$$D_{50} = 0.69^{1/n} \cdot a$$

$$= 0.69^{1/n} \cdot AR^p \text{ using (2)} \qquad (3)$$

where D_{50} is the value of drop diameter x such that 50 per cent of the
water comprised by the drops occurs with drops having diameters less than
D_{50}. Mean values of n, A, p found by Best, based on observations at six
different localities are 2.25, 1.30 and 0.232 respectively. Substituting
in (3) we have:

$$D_{50} = 1.10 \ R^{0.232}$$

A graph of D_{50} against R is shown in Fig. 1 which also shows the
rainfall rate ranges 1 to 5 and from which we obtain the following values
of D_{50} according to rainfall range.

Rainfall range	Range of D_{50} (mm)
1	0 - 1.35
2	1.35 - 1.97
3	1.97 - 2.35
4	2.35 - 2.75
5	about 3

It is stressed again that these are based on mean results and individual
rain experiences may differ considerably.

The numbers of drops of different sizes

Jones[3] by considering 147 drop-size distributions obtained at four
locations in the southern half of England has shown that the number of
drops $N \delta D$ per unit volume of diameter between D and $D + \delta D$ is related to
the diameter D by a relation of the form:

$$N = k \ e^{-\alpha D} \quad \text{for drop diameters greater than about 1 mm.}$$

The relationship, of course, is an average one and individual distributions
may depart widely from this curve. A similar relationship has been shown
to hold for measurements made in Canada[4].

In the above equation k and α are constants for a particular rainfall but vary with the rate of rainfall R according to the following expressions:

$$k = \frac{8934}{R^{0.21} \sinh (R^{-0.21})} \tag{4}$$

$$\alpha = \frac{4.00}{R^{0.21}} \tag{5}$$

when R is measured in mm/h, D in mm, and N is no. per m^3.

Marshall and Palmer gave the following values for k and α:

$$k = 7943$$

$$\alpha = \frac{4.1}{R^{0.21}}$$

The number N_1 of drops of diameter greater than 1 mm is then given by

$$N_1 = \int_1^\infty k e^{-\alpha D} \, dD$$

$$= \frac{k}{\alpha} e^{-\alpha}$$

The number N_2 of drops of diameter greater than 2 mm is

$$N_2 = \frac{k}{\alpha} e^{-2\alpha} \text{ etc.}$$

Using the values of k and α given by (4) and (5) above we obtain the distributions shown in Table I for various rates of rainfall; the bracketted values are those obtained using values for k and α given by Marshall and Palmer. The figures are not extended for diameters above 6 mm since there is evidence that drops of diameter greater than about 6.5 mm become unstable and break up. Attention is called to the great extrapolation used from the known data to obtain distributions at rainfall rates as high as 100 mm/h (4 in./h).

/Table

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TABLE I

No. of drops per m^3 of diameter greater than D for various rates of rainfall

R (mm/h)	D (mm)					
	1	2	3	4	5	6
2 (0.08 in./h)	72 (65)	2.3 (1.9)	0.07 (0.05)	0.002 (0.002)		
5 (0.20 in./h)	166 (146)	9.6 (7.8)	0.6 (0.4)	0.032 (0.023)	0.002 (0.001)	
10 (0.40 in./h)	289 (251)	25 (20)	2.1 (1.6)	0.177 (0.127)	0.015 (0.010)	0.0013 (0.0008)
25 (1.0 in./h)	560 (480)	71 (60.0)	9.7 (7.2)	1.27 (0.83)	0.17 (0.11)	0.022 (0.014)
50 (2 in./h)	844 (728)	145 (120)	25.0 (19.9)	4.30 (3.28)	0.74 (0.54)	0.127 (0.090)
100 (4 in./h)	1253 (1071)	274 (225)	59.9 (47.4)	13.11 (9.98)	2.87 (2.10)	0.627 (0.442)

Variation of drop-size distribution with height

Because of the lack of data on drop-size distributions above the ground it is impossible to do other than speculate on the way in which these distributions will vary with height. Many factors may operate to cause a change, the more important of which may be coalescence of drops of different sizes owing to their different rates of fall, particularly when the drops already of raindrop size fall through a layer of cloud comprised of numerous small droplets, and evaporation in the space between cloud base and the ground. Both these factors operate in such a way as to cause a shift in medians of the drop-size spectrum in the direction of larger diameters as the raindrops fall from the freezing level to the ground. An attempt to express this quantitatively has been made by Mason and Ramanadham[5] and the possibility that the number of larger drops may be increased by a factor of 5 or more between the freezing level and the ground is indicated at a rainfall rate of 3 mm/h.

In steady rain, therefore, in which the raindrops originate from the melting of snow at the $0°C$ isotherm, it would be expected that the median volume diameter and the frequency of occurrence of large drops would decrease with height, while above the $0°C$ isotherm most of the precipitation will be in the form of snow. In temperate climates this statement is probably true for the ranges (1) and (2) already mentioned and may possibly be true in the monsoon areas of India and Burma for part of range (3).

The greater rates of rainfall, however, in all parts of the world i.e. ranges (3), (4) and (5) and possibly also in temperate regions the

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higher rates of rainfall of range (2) (with the possible exception of the monsoon regions already referred to) are almost certainly associated with rainfall of cumulonimbus origin.   In some parts of the world where orographic features particularly favour it (e.g. mountain ranges) or where convergence of different air currents, (e.g. the inter-tropical convergence zone) takes place the cumulonimbus activity may be widespread and give the appearance of continuous rain, but elsewhere the rainfall of cumulonimbus origin will be localised.   In this type of rainfall water drops may be carried up in the supercooled state to heights well above the freezing level, and it is probable that large drops may be encountered at these heights.   Radar evidence supports this view in that the radar echo intensity, which is proportional to $\Sigma\ ND^6$, is often almost constant with height over a large interval of height which may extend well above the freezing level.   There is evidence to suggest that some large drops may be found at least to the level of the $-40^\circ C$ isotherm and that large precipitation particles (either solid or liquid) would be encountered on occasions even up to the tropopause.   Theoretical considerations suggest that there will be a decrease in the number of the largest drops with height so that, as in continuous rain, the median volume diameter will, on the average, decrease with height.   The structure of the cumulonimbus cloud is, however, ever-changing and the turbulence and magnitude of the up and down currents are such that a single travserse of such a cloud may encounter drop-size distributions differing widely with distance and changing rapidly with time.   All that can usefully be said is that it should not be assumed that large drops will not be encountered at any height in a cumulonimbus cloud.

The most violent cumulonimbus clouds, usually thunderstorms, frequently extend to the tropopause so that a chart of mean tropopause height (Fig.2) in various parts of the world will give an indication of the heights at which large drops or solid particles may be found associated with the higher rates of rainfall.

Similarly a chart of mean freezing level heights will give the heights to which raindrops may be encountered in the gentler continuous rains of ranges (1) and (2).   (Fig.4).

Since there is some laboratory evidence that liquid water will not occur in the atmosphere at temperatures below $-40^\circ C$ a chart of the height of this isotherm for April is shown in Fig.3.

Horizontal extent of rainfall of various intensities

(a)   Range 1   (0 to 0.1 in./h)

Rain areas associated with these low rates of rainfall are often very extensive and belts of rain, associated with fronts, 500-1000 miles long and up to 200 miles wide in their broadest part are quite common. In more extreme cases these belts may be as much as 4000 miles in length.

When conditions of wind direction and convection are suitable, rainfall, of orographic origin, may extend along the entire length of the windward side of a mountain chain, e.g. the Norwegian and British Atlantic coasts, the Alps, Pacific coasts of U.S.A. and Canada and especially the mountain chains of Asia in the Indian monsoon.   The breadth of such orographic rain is rarely more than 150 miles to windward of the mountain crests and is usually very much less.

(b) Range 2 (0.1 to 0.5 in./h)

In extra-tropical latitudes it is estimated that the extent of rain-fall in this range is unlikely to exceed about 150 miles, and perhaps 100-120 miles north of 60°N.   It is thought, however, that occasions when the horizontal extent was 100-150 miles would be fairly numerous.

For tropical latitudes see under Range 3 below.

(c) Range 3 (0.5 to 1.0 in./h)

Rainfall of this intensity is almost always associated with convective type clouds giving rise to showers and thunderstorms.   Individual clouds of this type are rarely more than 10 miles across but conditions may arise in which the clouds are so close together that, to an aircraft, the gaps between may be insignificant.   Such conditions may occur along a trough of low pressure (often accompanied by a cold front) and along a mountain barrier.   In the former case a belt of rain of this intensity may be 100 to 300 miles long, although its width would be unlikely to exceed about 10 miles.   In the latter case the most outstanding orographic effect is in the most intense phase of the tropical summer monsoon, when rainfall of this intensity may be occurring virtually everywhere along the southern and western slopes of the Himalayas and Yunnan Highlands for a length of 1500 miles or more.   In western India and west Africa also monsoon rains, probably of this intensity, may occur over areas 700 miles across.

Heavy rain, perhaps over an area 200 miles across, would also be expected with tropical hurricanes.

(d) Ranges 4 and 5 (over 1 in./h)

Rainfall of this intensity is thought to be limited everywhere to one or two neighbouring convection cells, and is unlikely to be found in an area exceeding 10-20 miles across at any time.   It should be emphasised, however, that rainfall of this intensity does occur even in the British Isles in association with heavy showers or thunderstorms, although its horizontal extent may often be very small.

Hail

Hail occurs only with convection type clouds - especially thunder-storms - and its occurrence and horizontal extent would therefore be similar to those for rainfalls of Ranges 3-5.   Judging from experience of aircraft traversing thunderstorm clouds, however, the horizontal extent of the hail area within such clouds may often be substantially less than that of the heavy rain area and will often not exceed 1 mile in diameter.

While the maximum size of raindrops is limited to about 6.5 mm, since drops of greater diameter would break up on falling through the air, this does not, of course, apply to the size of hailstones.   In extreme conditions, with vertical currents of high upward speed and large water content, hailstone diameters greater than 5 cm have been reported.   In thunderstorms in the British Isles stone diameters of 5-10 mm may occur quite frequently.

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3	R. F. Jones	Met. Res. Pap; London. No.453, 1948
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5	Mason and Ramanadham	Q.S.R. Met. Soc., 80, 388, 1954.

3.1 Discussion

Mr. L. K. C. Legg, Short Bros. & Harland Ltd.

I wonder if Mr. Murgatroyd could tell us if there is any vast effect arising from wind, especially gales, on the droplet size, and whether that would make the situation worse or better?

Mr. R. J. Murgatroyd

I do not think there is any great effect to be expected from winds at all, as the terminal velocity of the drops is very small compared with that of the aircraft. The only effect the wind can have is wind shear, which can decrease the height of the cloud belt but it is a very small effect.

Prof. G. F. J. Temple, Oxford University

Mr. Murgatroyd said that most of these observations were made on the ground: on the other hand we know that the radius of the drops changes as they are falling. Would he indicate what corrections and the amount of corrections which would have to be made?

Mr. Murgatroyd

The only information we have is that quoted by Mason[5] who took a distribution of droplets in a cloud and a certain population of cloud droplets. He considered the biggest ones falling and sweeping up the small cloud droplets as they fell. They also swept up the small droplets that they caught up with. They got to the base of the cloud and then he considered the evaporation of each size of droplet, the evaporation effect being bigger on the smaller droplet, to get his distribution on the ground. The big ones on the ground were increased by a factor of 5 compared with what they were at the freezing level. However, if you take cumulo-nimbus clouds with heavy vertical currents you would expect all the droplets to be quite large in the cloud as well as at ground level.

4 FLIGHT TEST WORK CONCERNING RAIN EROSION
F. J. BIGG, MECHANICAL ENGINEERING DEPARTMENT, R.A.E.

The purpose of flight testing

The three main purposes of flight test work are to provide:-

(i)   a comparison between the erosion obtained by ground testing and real atmospheric conditions,

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(ii) a comparison between several different materials under identical real conditions,

(iii) full scale test facilities; such as the effect of large radii of curvature, sweepback and other variables not reproducible on rigs.

The development of materials can best be done by controlled comparative tests on ground rigs, but flight tests are essential in order to correlate the erosion obtained by ground tests with that which actually occurs under flight conditions.

In addition the flight work extends the size range of the tests from the maximum radius of curvature of approximately one inch, set at present by the ground equipment, to the twelve inches or more of the nose radome.

Method of test, and recording equipment

The parameters associated with rain erosion are airspeed, the time in rain and the size and concentration of the raindrops. In flight work the pilot can determine the speed and the time, but some means must be devised to record the size and concentration, since the pilot's impression of the rain he has flown through, e.g. light, moderate or heavy, depends upon his experience of this type of work and although this is a useful guide it cannot be used for comparative assessments. For example what is commonly called heavy rain in Britain would be considered light or moderate rain in Singapore. It is also difficult to differentiate between hail and rain.

The size of raindrops can be measured in flight by the sooted slide technique. In this method a 2 inch square wire gauze approximately 40 mesh to the inch, is sooted with paraffin smoke and is exposed to the rain for a short time in flight. The raindrops strike the gauze and remove the soot as they pass through it. Unfortunately this method cannot be used at high speed since airflows above 200 m.p.h. remove the soot. There are numerous water concentration meters in use for low speed work and these also would fail at high speed with large droplets.

The size of raindrops can be measured on the ground by the sooted slide technique or by the stains produced on filter paper dusted with Rhodamine dye, and in addition the rate of rainfall can be recorded by special rain gauges. Hence one solution to their measurement in erosion flight tests would be to make these measurements on the ground whilst the aircraft flies overhead. This has been tried but was found to be unsatisfactory because of the vagaries of the weather. The testing is limited to the airfield so that other flying is interfered with, particularly while the aircraft makes high speed runs. In this country heavy rain appears to fall over a limited area usually away from the ground measuring instrument.

The development of a flight instrument is therefore proceeding for recording the size and number of droplets striking a forward facing area of the aircraft. The apparatus consists of an electrically driven drum 6 inches in diameter situated close to a 2 inch diameter hole in the nose of an aircraft. A metal section on the surface of the drum seals off the hole in the nose for take-off and landing, its position being indicated to the pilot by a light in the cockpit. Before flight work can proceed it is essential to make these measurements on the aircraft. The obvious place to measure is in the nose of the fuselage. A Meteor has been allocated for rain work.

For test purposes a recording surface such as wax, wax paper, typing paper or a thin metal foil is wrapped round the drum and secured to it. In flight when the aircraft enters rain the drum is slowly rotated so that each raindrop that strikes the surface can make a mark. A calibration of the size of mark given by a known size raindrop at a given airspeed on the recording medium can be obtained using the compressed air gun technique[1]. From this calibration the size and number of drops striking the nose area can be made from the drum record.

From a selection of the best type of marking medium it is hoped to develop a continuous strip recording instrument so that many traverses of the same rainbelt can be made and recorded thus increasing the time of exposure of any test samples on the aircraft.

Once we can measure the size and number of strikes test samples for rain erosion flight work can be attached to the leading edges of the wings or around the nacelles. Alternatively, sets of cylinders of different materials and varying diameters (say 1, 2 and 3 inches) can be made up for exposure tests at high speed. By this work a direct comparison of different materials can be made under identical natural rain conditions. This information will be most useful for correlation with ground rig results.

There is still the problem of raindrop strikes on the edge of the hole in the Meteor nose. Presumably only part of the raindrops will strike the surface of the drum, but we hope to be able to recognise them as edge hits and to make suitable corrections.

Future development

The drum was first located at the rear of a tube in the nose of the Meteor. The rain had therefore to travel down about 3 inches of this tube before striking the drum. As poor marks were obtained on the wax it was concluded that perhaps the drops were breaking up before striking, and as a result we moved the drum forward to its present position as close as possible behind the hole. However if droplets can be broken up by a 3 inch layer of stagnant air this may be developed into a means of erosion protection.

It is hoped to arrange for some flash photography in flight to explore the possibility of recording rain strikes, and possible distortion of the droplets.

Once a satisfactory recording medium has been evolved continuous recorders can be designed for other aircraft and tropical rain tests can be made.

The tests may be extended to very high speeds.

REFERENCES

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4.1 Discussion

A Speaker

Can Mr. Bigg explain why he found the variation of extent of rain erosion along the leading edge?

Mr. Bigg

I can only explain what I have observed. It appears that the erosion is a function of the radius of curvature which varies along the leading edge.

Mr. A. A. Fyall, Chemistry Department, R.A.E.

It may possibly be that, due to the effect of the aerodynamic airflow round the nacelles and other parts, you might not in fact get any strikes at all. I believe some N.A.C.A. papers have been written on the striking of drops and I think under certain conditions some areas will not be affected at all because of the aerodynamic shape.

Prof. Temple

One of the earliest papers was by G. I. Taylor on de-icing.

Mr. Fyall

It might be proper to point out here that there is definitely a given angle of attack at a certain speed beyond which no rain erosion occurs, e.g. at 500 m.p.h. erosion occurs from direct impact (90°) down to an angle of attack of 30° between the line of flight and the tangent to the surface. In tests of several hours duration there was little or no erosion beyond this angle.

Mr. Radcliffe, G.W.(E) M.O.S.

Would Mr. Fyall please state whether the angle is one of incidence or a cone angle?

Mr. Fyall

The total included cone angle would be one of 60°.

Mr. Legg, Short and Harland

I think this is a very important point. Obviously when the raindrop strikes at the top of the radome you are well into the boundary layer and the raindrop will strike the boundary layer before the surface and may disintegrate in the process.

Mr. Bigg

The flight work is done at fairly high speed and the recording drum is located as far forward as possible in the nose in an attempt to get direct strikes.

Mr. Legg

Has it been entirely substantiated that this is the worst place?

Mr. Bigg

Yes.   Flight in rain quickly removes the paint from the nose of the
Meteor.

Prof. S.Tolansky, London University (Royal Holloway College)

Since you have a flexible recording device, is it possible to intro-
duce two slots and bring your flexible strip outside instead of inside?
The flexible strip will actually move over the surface and you probably would
get something much more realistic.

Mr. Bigg

I presume that would mean using a roller of some material such as hard
rubber in the nose round which the flexible strip could be driven.   We have
tried typing paper to record the strikes but the paper will not stand up to
the aerodynamic forces.   At the moment we are considering the use of shim
copper which is very soft and I think we will get small dents on it.   There
is still the problem of whether a drop when approaching this surface still
stays spherical or whether the air forces distort it to a saucer shape or
break it up before it actually strikes.

Mr. R. C. Gilbert, De Havilland Aircraft Co. (Christchurch)

How long have you worked on this job because I remember seeing the
damaged radome now on show about three years ago?

Mr. Bigg

I think the first recorded damage was observed during the last war
on a Beaufighter where the radome was smashed either by hail or heavy rain
and investigations have proceeded from that time.

Mr. Gilbert

You still have not obtained a satisfactory method of recording a
raindrop?

Mr. Bigg

Yes, that is what it means.   As Murgatroyd has said the rain on the
ground is different from the rain at altitude and therefore a flight
recorder is necessary.

Wg. Cdr. Rowson, G.W. Dept., R.A.E.

We have a statement from Chemistry Department, R.A.E. stating that
there will be little or no erosion for angles of strike of 30° or less,
i.e. an included angle of 60° on a cone.   Does this refer only to work
done at 500 m.p.h. and not to supersonic flight, as it was not stated
categorically at which speeds this applied.

Mr. E. J. Russell, Chemistry Dept., R.A.E.

I shall be dealing with the American experience in regard to super-
sonic flight and will be covering that point.

<u>Mr. W. H. Swire, B.B. Chemical Co. Ltd.</u>

Are you sure that, when you have got a raindrop hitting the surface of a smoked screen you can tell anything from it? Is it possible for us to see some of your recordings?

<u>Mr. Bigg</u>

Yes, the raindrops remove the soot and leave a mark characteristic of the original drop size. However, the smoked screen is only effective at speeds up to approximately 200 m.p.h. and is therefore inapplicable in the high speed case. No flight records are available since the new technique is in the early stages of development.

<u>Prof. Tolansky</u>

I will answer that question later when I show you some slides of the damage done by single raindrops. I have been studying surfaces by interferometry and the effect of single impact by raindrops. This will be an answer to your question: each drop produces damage.

<u>Mr. Swire</u>

Can you tell the size of the raindrops coming through the aperture from the mark that you obtain?

<u>Mr. Bigg</u>

Yes, you will get a continuous record from the drum which we hope will show rings. Knowing the speed we can then calculate the size of the drop which caused the depression.

<u>Mr. D. C. Jenkins, Mechanical Engineering Dept. R.A.E.</u>

By means of our impact gun technique we have a means of calibrating these marks obtained in flight.

<u>Mr. C. A. Wagstaffe, D.L.A.R.D.(1), M.O.S.</u>

We have had an adequate description of this drop measuring device but one has a feeling that it is a little crude and some people here would like to know what development work has been done. We have had this problem for many years, and I believe that all kinds of devices have been tried for observing this drop size and distribution. Could Mr. Bigg just mention one or two of the more obvious ones? I had in mind the use of a microphone. I have a feeling that we have not got very far over a long period of time.

<u>Mr. Bigg</u>

Droplet microphones have been tried but they have proved to be of no use. I think the main trouble with the microphone is the noise that one gets from the actual air loads on it. You cannot distinguish the drops. You can in a laboratory allow drops to fall on a microphone to record their size but in flight there is too much background noise.

<u>Mr. Wagstaffe</u>

Did not the Met. Office have a large programme some years ago for developing apparatus for that purpose or did that come to nothing?*

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* The Meteorological Research Flight at R.A.E. experimented with a "rain drop" microphone developed by R.R.E. Malvern but found is unsatisfactory.

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Prof. Tolansky

I hope that my slides will show that provided one has a good optical technique, it is quite easy to see the effect of single drops on a suitable surface. What ought to be a very ready answer is a precision optical approach to record not only the number of strikes but also an indication of the size of the drop.

Mr. H. C. B. Thomas, Head of Mechanical Engineering Dept. R.A.E.

I would not like you to run away with the impression that the R.A.E. has been working on this problem for a great number of years. This is not so. As far as a number of Departments in the R.A.E. are concerned it is only in the last 5 years that the problem has been dealt with seriously at all. It had been dealt with as a problem of preventing unsightliness of the aircraft rather than of preventing damage. It is only in the last few years that Chemistry and Mechanical Engineering Departments have made a detailed study, because the increasing high speed of aircraft has led to greater damage.

Mr. A. Cooper, Expanded Rubber Co.

I would like to ask Mr. Bigg whether he has considered measuring the size of the drops photographically, not at the nose but at the side of the fuselage. The erosion will not occur at the side but after all you would be travelling at right angles to the rain and you can presumably record this on a cine-camera. Further, you would only be a few feet away from the point of impact and I should think it would make no difference at all to the results.

Mr. Bigg

As I said in my lecture, I hope that we will have photography to observe strikes at the wing root, but I think you have got to have flash photography because of the velocity effects so that the raindrops may be stopped in motion, otherwise the picture is a blur.

Mr. Fyall

I have in fact done some photography of drops and it is very difficult unless you have a flash technique and also a dark background. It would be very difficult to do in the air and you would probably have to do it at night.

Mr. Murgatroyd

A lot of work has been done on raindrops using a camera by Elliot at N.A.E., Canada. It has been going on for many years and it has not had a lot of success. There are several optical reasons; first you have, as it were, to stop the drops in flight by rotating a prism in front of your camera; second you have got to have a very narrow depth of focus for accurate alignment of your optical system, and third the droplets fall so slowly that you would have a great length of film with only two or three droplets on it.

Mr. J. W. Denson, Goodyear Tyre & Rubber Co. (G.B.) Ltd

Could Mr. Bigg give an estimation of the number of strikes per second on an area of say 1 sq in?* The reason I am asking is to ascertain at what

* **Number of strikes per square inch on aircraft flying through rain**
From the analysis of the number of drops present in a cubic metre of air, given in Mr. Murgatroyd's paper; (continued bottom of p.19).

speeds your recording drum would be rotating to avoid two strikes in the same spot.

Mr. Bigg

At the moment we have a 6 inch diameter drum rotating at 3 r.p.m., but this could be speeded up if necessary.

Mr. D. N. Hunter, D. Napier & Son, Ltd.

Mr. Bigg, have you established any standard material for rain erosion yet - a standard of comparison e.g. an aluminium alloy, in order to compare the effect on different materials?

Mr. Bigg

We have not gone into that yet in flight tests.   This will be the first problem we have to tackle.

5   SIMULATED TESTS

DR. R. N. C. STRAIN, CHEMISTRY DEPARTMENT, R.A.E.

Conditions of test

For the development and testing of materials or special assemblies flight testing with aircraft or rockets is a very slow and uncertain method. It is therefore necessary to have a simulated test in which the conditions are as near as possible to those in actual flight.   While no particular test can be claimed to simulate all the flight conditions, methods have been developed which reproduce the more important conditions and which produce erosion similar to, and of the same order as that obtained in flight.   For the wide adoption of any particular material, flight testing must be the final answer, but great caution must be exercised with a negative result in this country, because of the low rainfall rate, unless the speed and rain conditions encountered are actually recorded.

Rainfall mm/h	2	5	10	25	50	100
No. of drops/cubic metre	75	170	315	642	1014	1607

These figures show that the number of drops is not a function of rate of rainfall since the volume median diameter increases with increasing rate.

In Great Britain, 2 mm/h is considered fairly heavy rain.   Assuming that the aircraft speed is V ft/s then:-

$$\text{No. of strikes/sq in./s for 2 mm/h rainfall} = \frac{V}{71}$$

Assuming a hole 2 inches in diameter in the aircraft nose and a recording drum, 6 inches in diameter and 2 inches thick and rotating at 3 r.p.m.

$$\text{No. of drops/sq in. of record} = \frac{V}{42.6}$$

Thus, at 400 m.p.h.,

$$\text{No. of drops/sq in. of record} \sim 14$$

The main conditions to be simulated or controlled are:-

(a) Speed of sample relative to the water drops

(b) Shape of sample or angle of strike

(c) Aerodynamic conditions around the test sample

(d) Water drop size and rate of rainfall

No reliable simulated test has been employed in which temperature and pressure have been other than ambient ground conditions, mainly because of the engineering difficulties involved.

The effect of temperature is less important (excluding of course degradation by kinetic heating in flight when not in rain) and so far at the R.A.E. no significant difference has been found in the results obtained when testing in the range -5°C to +20°C. Little critical evidence is available regarding the effect of reduced pressure but it is known that serious erosion has occurred in flight when the pressure was below normal.

The speed at which rain erosion becomes significant is much greater than the terminal velocity of a rain drop so that the angle of strike is little different from that obtained if the rain drops were stationary. It is therefore convenient to simulate relative motion in one direction only. The angle of strike is the angle between the line of flight and the tangent to the surface. The tests can be divided into two types, in which the rain drop or the sample is stationary and the other is moving.

Water drop moving and test sample stationary

Fig.5 gives the terminal and shatter velocity for drops of different sizes.

Water jet method

Water is forced through a jet at high pressure against the test sample. Speeds up to 500 m.p.h. have been recorded but the drop size obtained is very small.

Water jet in wind tunnel

This method is designed to prevent the drops from shattering by injecting them into an air stream having the same velocity. For a 2 mm drop the critical relative velocity is ≑ 55 ft/s; this is difficult to maintain during its flight from the jet to the test sample. To avoid the difficulty of projecting a water drop at a precise velocity Bigg[1] has suggested that the drop be allowed to fall under gravity in a vertical wind tunnel in which the air speed increases progressively relative to the drop but does not exceed its shatter velocity. Under these conditions the minimum height S_{min} of the tunnel can be calculated from the formula

$$S_{min} = \frac{V^2}{2g}\left[\frac{1}{1+\left(\frac{V_S}{V_T}\right)^2}\right]$$

where V = final velocity of drop; V_s = shatter velocity and V_T = terminal velocity of drop.

Thus for a 2 mm drop to reach 500 m.p.h. (733 ft/s) the minimum height (S_{min}) would have to be 951 ft.

Water drop gun

In this method a single drop occupying a cavity in the front of a plastic 'bullet' is fired from a gun: the plastic bullet which is aimed at a small hole in a steel plate strikes the plate, but the hole is sufficiently large to allow the drop to pass through to the sample on the other side. One of the main difficulties of this method is to prevent broken pieces of bullet passing through the hole and striking the sample.

Water drop stationary and sample moving

Gun techniques

A technique has been developed where the sample is attached to the front of a bullet and fired at a drop suspended on a synthetic cobweb. This technique will be described in detail by Mr. D. C. Jenkins and will lend itself to supersonic speeds. The technique is essentially a single drop method: its extension to multiple strikes would mean the provision of a very long track of real or artificial rain to get a few seconds of simulated conditions. For large test samples a rocket propelled vehicle running on a track may be necessary.

Whirling arm techniques

In these the test samples are attached to the outer portion of an arm or conventional propeller, set at zero pitch, which is rotated in an area containing simulated rain. This method is the one which has been most widely used as it simulates most of the important conditions and can produce continuous and uniform erosion.

The choice of whether the arm should rotate in a vertical or horizontal plane is often one of available facilities. The test rigs at Cornell University and Napier and Sons both use a zero pitch propeller spinning in a horizontal plane with the 'rain' falling vertically on to it, the test samples being attached to the leading edge near the tip.

At the R.A.E., the original method of test was a wooden 'Bulldog' propeller spinning in a vertical plane with water sprayed from three swirl atomising jets set at right angles to the track of the samples. It was clear however that by this method the drop size and distribution of the drops could not be made to approach that of real rain: an alternative method was therefore developed.

R.A.E. new whirling arm test rig

This is a development of the conventional propeller rig in which the blade is replaced by an arm of circular section with two cylindrical test samples fixed at each end and at right angles to the arm. The arm, 9 ft 6 in. long, is made of forged S.97 steel which was hardened and tempered to give maximum strength. This shown in Fig.6.

It was originally intended that the arm should be rotated in a vertical plane with the 'rain' falling vertically downwards from 120 water jets supplied with water from a special double bottomed water tank. The jets were fabricated from hypodermic tubing and connected to the upper

compartment of the tank which was filled with filtered water to constant depth. Each jet was surrounded by an air annulus attached to the lower compartment which could be adjusted in relation to the position of the tip of the jet. Compressed air fed to the lower portion of the tank and to each annulus controlled the drop size issuing from each jet. In practice this method of producing drops of controlled size was very satisfactory but with the arm rotating at 1472 r.p.m. (sample speed of 500 m.p.h.) the erosion was very erratic and it was subsequently found to be less severe than that found with samples under more realistic conditions. The cause of this irregularity was found to be the air, which is thrown outwards from the hub of the arm, and which deflected the drops away from the test area. The use of baffles extending from, and at a tangent to the path of the specimens did not significantly reduce this effect. This trouble is not peculiar to the circular section of the arm and samples since a propeller with zero pitch behaved similarly.

When it was realised that the drops could not be made to enter the test area against the outward airflow, a technique was developed in which the drops were projected radially outward from the hub area of the arm from the edge of a disc rotating in a plane parallel to that of the arm as shown in Fig.7. This sketch is to scale and shows the trajectory of the drops leaving at a speed of 22 ft/s from a 2 ft 4 in. disc spinning at 185 r.p.m.

The lower portion of Fig.7 shows how the spinning disc has to be adjusted in relation to the arm in order to allow for the air which is thrown out radially from the hub which deflects the drops. This adjustment has been made by trial and error and has to be done for each test speed. Figs. 8 and 9 show typical calibration samples of good and poor quality glass fabric/polyester resin respectively on which reasonably uniform erosion does occur. These samples also show the partial shielding of the sample by the arm at the inboard end.

The spinning disc technique is an extension of a method devised by Walton and Prewett[2] who have investigated the production of homogeneous sprays and mists by means of a disc spinning in a horizontal plane. In this case the diameter of the drop produced is represented by the formula

$$d = k \frac{1}{\omega} \sqrt{\frac{T}{D\rho}}$$

where d = droplet diameter; D = disc diameter; ω = angular velocity of disc; T = surface tension of the liquid; ρ = density of liquid. The average value of k was found to be 3.8.

Tests with a 1 ft and 6 ft diameter disc have shown that this formula holds reasonably well when the disc is spinning in a vertical plane and a value of k = 3.7 for the 1 ft disc has been obtained. For the production of drops 2 mm diameter a disc 2 ft 4 in. diameter revolving at 185 r.p.m. has been adopted: this size was found to give the necessary velocity to the drops to enable them to reach the test area irrespective of the angle at which they left the disc.

When uniformity of the drop distribution had been achieved, the rate of rain fall and drop size were measured by sampling in an area close to the path of the sample when the arm and disc were running at their correct speeds.

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Provided the spinning disc is sheltered from excessive natural wind, uniformity of results can be obtained.

The present arm absorbs 500 h.p. at a Mach number of 0.7 and it has been calculated that on an alternative spinning tower, which has 3800 h.p. available, it could be made to reach 0.9 Mach. It is not proposed to test it at this speed but to make a new arm with less drag with the aim of reaching Mach 2.0. In order to reach this high test speed, the high bending stress on the samples will be minimised by making the arm much bigger and a design study has been completed for one 16 ft long. It will probably be necessary to use several small spinning discs in order to get even distribution of the rain drops. The arm will be lenticular in section to provide low drag characteristics and to aid manufacture. The half section of the arm will be similar to an oblique cut from a cylinder so that the arm will taper in span and thickness as it goes outboard; by this means it is hoped that it can be turned and finally ground to high precision on a lathe.

The arm will be made of steel and has been stressed to carry a load of $2\frac{1}{2}$ lb at each end, this weight to include the sample, sample holder and counterpoise. It is estimated that the arm will have a final weight of around 1000 lb. The exact design of the sample has not yet been decided but it is proposed to use small radius cylinders in the transonic range and at higher speed to use something approaching a lenticular section.

REFERENCES

No.	Author	Title, etc.
1	F. J. Bigg	R.A.E. Tech. Note No. Mech.Eng.187, 1954.
2	Walton & Prewett	Porton Tech. Paper 14, 1947.

6   FUNDAMENTAL STUDIES USING THE SINGLE DROP METHOD
     D. C. JENKINS, MECHANICAL ENGINEERING DEPARTMENT, R.A.E.

Introduction

An essential part of the study of rain erosion is to find out how the surface damage is initiated and then extended by the impinging rain drops. To do this it is necessary to study the effect of the impact of single drops. Because of the low relative speeds at which water drops shatter, difficulty is experienced in accelerating a water drop of the size occurring in rain to the speeds at which surface erosion occurs. The alternative method of shooting the surface at a stationary drop has been used in an apparatus described below which has been developed at the R.A.E.

Description of apparatus

Fig. 10 shows a diagrammatic arrangement of the apparatus.

The material specimen forms the flat nose of a projectile which is fired at a given speed by the air gun. The specimen surface strikes a

rain drop suspended on a very fine web. The projectile then enters an energy absorbing tube where its kinetic energy is absorbed by passing through and deforming soft aluminium washers. The holes in the washers are larger than the diameter of the specimen so that any imprint caused by the rain drop impact is undamaged.

A speed of 800 ft/s is achieved by the prototype apparatus but higher speeds could be attained by suitable design.

Drop suspension

A 2.5 mm diameter drop suspended on the web is shown in Fig.11. The web is made from Perspex dissolved in aniline which can be drawn out as very fine filaments between two cork faces. For trying out various theories liquids other than water can be used. Mercury has been successfully used giving a large range of density and surface tension.

The water drop and web can be frozen to give ice spheres.

A flash photograph of the projectile about to strike the water drop at a speed of 770 ft/s is shown in Fig.12. The column of air preceding the projectile has blown away the web leaving a roughly spherical shaped drop which is struck by the projectile before it has time to fall.

If the rain drop is placed too close to the gun muzzle the air blast may be sufficient to shatter the drop. A typical shattered drop is shown in Fig.13. and consists of fine droplets blown away from the central mass of the drop.

Marks made in aluminium by single drops

The mark made in solid aluminium by a spherical water drop 2.5 mm diameter at 800 ft/s is shown in Fig.14(a). The impression consists of a single depression, of Brinell hardness type, of depth 1/1000 inch approximately. The reason for the difference in type of depression between Perspex and aluminium is not clear.

The mark made by a single shattered drop of 2.5 mm diameter at 800 ft/s is shown in Fig.14(b). Instead of a single depression in aluminium the shattered drop causes a series of indentations, some of which have the appearance of pits rather than the smooth depression of the spherical drop. The depth and degree of scatter of these indentations depend on the extent of break-up of the drop.

The difference in type of mark made between a round and a shattered drop suggests that rain drop shape may be one important factor in the rate at which erosion occurs, and that a more extensive knowledge of the shape of rain drops impinging on aircraft surfaces in flight is necessary.

Marks made in Perspex by single drops

Fig.15(a) shows the mark made in Perspex by a spherical water drop 2.5 mm in diameter at 800 ft/s. The impression is characteristically an annular depression. Similar impressions have been obtained in wax. The reason for this depression is not known, but it has been suggested as being due to an annular region of maximum impact pressure.

Fig.15(b) and 15(c) are photographs taken by Mr. Barnett of Professor Tolansky's Department at the Royal Holloway College. Fig.15(b) shows the fine crazing crack system surrounding the annular crater in Perspex, shown in Fig.15(a). The scale is given by the two long surface scratches running through the centre which are approximately 0.05 mm apart.

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Fig.15(c) shows in detail some of the fine cracks. The side of the crack furthest from the centre of the annulus has been bent over by the rapid radial wash of the bursting drop. According to an American analysis of this problem the radial wash in this case would be 1300 m.p.h. and the maximum impact pressure 27,000 lb/sq in.

These illustrations given some idea of the type of information that can be obtained from a single rain drop apparatus and show that even a single rain drop can cause damage.

Investigations proposed with this type of apparatus include:-

1 Detailed photographic study of the break-up process on impact.

2 Study of impact pressures, by replacing the specimen by a piezo-electric crystal.

3 Effect of physical properties of the drop i.e, shape, size, density and surface tension.

4 Effect of physical properties of the material i.e. surface finish, hardness, elasticity etc.

5 Effect of speed, for which purpose higher speed guns are being developed.

7   THE DAMAGE ON PERSPEX CAUSED BY IMPACT WITH A WATER DROP
       PROFESSOR S. TOLANSKY, ROYAL HOLLOWAY COLLEGE, EGHAM.

Together with Mr. T. R. Barnett, precision optical studies have been made upon three impacts made on Perspex. The Perspex samples were fired by Mr. Jenkins from his air-gun at single $2\frac{1}{2}$ mm diameter water droplets. Three separate impacts were made, on different samples, with velocities respectively of 800 ft/s, 680 ft/s, and 550 ft/s. The recovered Perspex samples were examined by a variety of microscopic techniques which included direct microscopy, phase contrast microscopy, multiple-beam interferometry and light-profile microscopy.

Consider first Fig.16(a) (x 14) which shows a micrograph of the mark left on Perspex when impact is at 800 ft/s. There is a ring-shaped mark, surrounded by a further annular region, and this is succeeded by what looks like crazing. The topography of this feature will be discussed in detail later.

Fig.16(b) (x 14) shows the impact figure at 680 ft/s, and again there are the two concentric features, surrounded by crazing. Fig.16(c) (x 20) shows the less marked effect for a velocity of 550 ft/s.

When these surface features are examined by multiple-beam inter-ferometry much is revealed. This technique will first be very briefly outlined. When a surface with a complex microtopography is matched against an optical flat and illuminated with parallel monochromatic light, then localized interference fringes form. These constitute, in effect a topographical contour map of the relief of the surface, the individual neighbouring fringes (contour lines) corresponding to height changes each of half a wavelength (say 10 micro-inches).

Now in multiple-beam interference methods the fringes are optically sharpened to a very high degree, such that height variations of only a two hundredth part of a light wave (say 1/10th micro-inch) can readily be

detected and measured. These techniques involve refinements, the details of which can hardly be discussed here. Two principal types of multiple-beam fringes are in use. The first is monochromatic multiple-beam Fizeau fringes, which give a contour map, exactly analogous to the familiar contour maps of geography, the contour lines corresponding to 10 micro-inch height changes. The second method, which I have called fringes of equal chromatic order, uses white light and gives a sequence of fringes, each of which (in its own wavelength) is an optical profile over a selected line section of the object. In the present case the line section selected is diametrical. We shall consider some of the interferograms.

Fig.17 shows the multiple-beam Fizeau fringe pattern for an 800 ft/s impact. This striking picture is full of information. Taking an approximately central fringe and approaching say from the right, the surface rises slightly, (say, 10 micro-inches). Immediately following this is an annular depression region (some 30 micro-inches drop). The surface then rises up almost to the initial level, although not quite. The central disc has a shallow depression, perhaps some 5 micro-inches deep at the centre. There is also some circular asymmetry.

It will particularly be noticed that the outer fringes surrounding the main concentric circular patterns, are broken and jagged. This is where they run across the crazing region. One can see, without making measurements, that the crazing consists of saw-like steps, which are remarkably shallow, being of the order of 1 or 2 micro-inches deep, but not much more.

It is quite clear that so detailed a picture will repay careful precise study. Attention is specifically drawn to the extensive area of crazing, or cracking, as revealed by the fringes, that is, relative to the circular impact depression. The depression itself has a most peculiar shape. It would seem to suggest that impact produced a depression and this was followed by a central recovery, leaving the observed annular ring-shaped hollow, with a central disc recovered back almost to the original level.

As an example of the use of the fringes of equal chromatic order, Fig.18(a) shows these for a diametrical section of an 800 ft/s impact. Without going into detail, the enormous magnification in depth should be noted. When projected on to the lantern screen, these fringes are some 10 inches apart. Yet they represent height differences of 1/100,000th inch. The magnification on the screen is thus about one million. It should be recognised that such magnifications are indeed not by any means empty magnifications. For under the best of conditions it is possible to resolve 1/25th micro-inch, i.e. on the screen this would represent a distance of 1/25th inch. Thus magnifications of a million have very real resolution and are not merely empty "blowing-up", since merely 1 millimetre on the screen is resolvable.

Fig.18(b) shows the corresponding fringe pattern for the 680 ft/s and Fig.18(c) that for the 550 ft/s impact.

Magnifications are, in these two figures, so enormous that the relatively poor state of surface polish (poor in terms of the precision under discussion) gives the fringes a ragged appearance which is deceiving. Indeed to exploit fully the available resolving power very special care has to be taken with the micro-polish of specimens. This was not the case in the samples shown herewith, which are crudely polished only.

As a final picture, Fig.19 shows the crazed region for the 680 ft/s impact, this time taken with phase-contrast microscopy.

An important conclusion is the extent and character of the crazed crack-region. It is not the central drop region but the larger crazed region which is most dangerous from the view point of subsequent breaking. The actual crack depths may well be shallow, yet breakage will probably be initiated there because of the high stresses. Peaks and valleys are sharply defined and fine hair cracks may well extend considerably down below the surface, as the very fringe shape seems to hint at.

These photographs give a positive reply to the question already raised as to whether a single raindrop can make an easily detectable mark. It is quite clear indeed that at the higher velocities quite a considerable mark does appear. A detecting device for registering raindrop concentrations met at high speed, which might easily function well, would be to run a plastic strip continuously past an aperture exposed to the rain and then later to examine it microscopically with the right type of illumination. There seems little doubt that individual droplet impacts could be separately identified and counted. This is certainly the case for the droplets of the size investigated here.

7.1 Discussion on Sections 5, 6 and 7
Mr. K. W. Hetzel, Vickers Armstrong Ltd., Winchester

I would like to ask if Dr. Strain has looked into the method of test used at Convair in the United States where a bullet is fired at raindrops. This seems a very elegant technique.

Dr. Strain

The bullet technique used is really an extension of the method used by Mr. Jenkins, if you mean a bullet shot from a gun through rain.

Mr. Hetzel

Yes, with various simulated radomes etc. on the front.

Dr. Strain

Yes, we have considered that here, and Mr. Russell will be mentioning the American work in his paper.

Mr. E. M. Goacher, Vickers Armstrong Ltd. (Weybridge)

It seems to me that there must be quite a lot of heat generated with the amount of energy absorbed into the plastic laminate. I would like to ask first whether the lecturers consider that this has any effect upon the erosion, and secondly, a practical point, is it worthwhile studying not the material which has been subject to erosion but the material which has actually been eroded away, if you could collect it together and have a look at it? Has anybody done that and if so what form did the eroded particles take?

Dr. Strain

On the question of heat from the drops, we do find some heating of the sample but you also have water cooling present. At 500 m.p.h. the sample is only slightly warmer than at the start. We have never found any eroded particles.

Mr. D. A. Woodley, Armstrong Whitworth Aircraft Ltd.

It is difficult in these interim question periods to avoid anticipating later discussion. It is perfectly obvious that a great deal of work has been done on this subject, as we have already seen, and I think that most of us here will know that it is a very real problem up to 600 m.p.h. or so. I am a little bit worried by the lectures today which show that the test rig and other work being done, which has been described by the recent lecturers, seems to anticipate 500 m.p.h. as being the limits of their test. Do we already know that the supersonic pressure pattern is such as to make 500 m.p.h. critical? It seems to me that a lot more will have to be done and can I in fact be informed now whether a lot more is being done? I was a bit worried about Dr. Strain's opening sentence in his paper that testing with rockets is very slow. I should have thought this method extremely certain and very rapid in the way of an ad hoc demonstration of this problem. Can I be reassured that something is going on?

Dr. Strain

With regard to the 500 m.p.h. test, this is a very good one since very few materials stand up to it. Most of the hard brittle materials only last a few minutes at 500 m.p.h. so this test is useful for initial sorting.

The rocket technique is a very slow one for, having shot your rocket, you have got to recover it. You also have to wait for rain, so that you can only get a few seconds of test per month. There are other supersonic methods of test which will be dealt with later.

Mr. Woodley

Yes that is quite true, but a lot of us are only interested in vehicles which have only a few seconds flight and do not always work in rain. We are very interested in whether they work long enough and well enough to do the job that they are designed to do.

Dr. Strain

We are covering the rocket technique, firing whenever we can, which is not very often. If we get a supersonic test rig we will be able to get all the answers on all the materials with certainty. I think it is quite true to say that the drop size distribution in any cloud is irregular, so that flight testing gives erratic results.

Dr. Megson

Is your question really directed to finding out whether we are doing anything at supersonic speed or whether we are confining ourselves to 500 m.p.h.?

Mr. Woodley

Essentially so, yes. Are we in fact doing a fair amount of ad hoc flight work to assess the real problem and what we can do about it? What sort of cone angles do we really want and will the materials in fact achieve the limited life that we are after without interfering with other problems, electronic and otherwise?

Dr. Megson

Dr. Strain has answered the question in one part. Such work as we can do in actual flight is going on but we are also trying to put up a

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simulated rig and we hope to get a lot of information out of that.   As
Dr. Strain said 500 m.p.h. is severe for anything we have tried.

Mr. J. H. Phillips, ADGW (G & C) M.O.S.

I would like to come back to Mr. Goacher's question about temperature.
One would tend to think that, without doing any preliminary arithmetic, the
annular ring might in fact be a "frozen ripple" structure and the cracks
are the result of the ripple attempting to go through unsoftened material.
I wonder if a little arithmetic could bear that out?

Dr. Strain

I am afraid I cannot do the arithmetic on the spot (Laughter).   There
is a considerable amount of energy in each drop at 500 m.p.h. but it is a
fact that we do not get much heat on the rain erosion rig.

Mr. J. H. Phillips

You might get a lot of very local heating which is not a lot over the
whole sample.

Dr. Strain

Yes, but in the case of aluminium on Mr. Jenkin's rig you get a
depression formed which is distinctly more mechanical than thermal.

Prof. Tolansky

The fact that the effect of a steel ball impact is cracking, would
suggest that shock is responsible.   The fact that the high speed of the
water produces a depression in Perspex might suggest that melting or
softening was responsible for the depression which is rather a complex one.
So it may be that temperature has something to do with the production of
the depression but I think the cracks are probably due to shock.

Mr. G. B. Evans, De Havilland Aircraft Co. (Christchurch)

Surely if we refer to the work by Bowden and Tabor on friction we
can recall that very high local temperatures may occur although the overall
surface temperature rise recorded is very small.

Dr. Strain

I was actually thinking of overall temperature as produced by kinetic
heating without the rain.

8   CAVITATION AND ITS APPLICATION TO THE PROBLEM OF RAIN EROSION
     H. G. STUBBS. THE PLESSEY CO. LTD., CASWELL RESEARCH LABORATORY.

With the development of new materials for radome and structural
purposes, particularly the former, there is an obvious need for a rapid
laboratory method for determining their resist_nce to rain erosion.   The
present investigations are concerned with this development.

An important feature of rain erosion is the extremely high local
pressures that are developed at the moment of impact.   American evidence,
is that the rate of erosion rises rapidly with increase in impact velocity,
probably according to a 6th or 8th power law.   It is possible that at the
speeds now encountered there is incomplete deformation of the rain drop

before the majority of the relative kinetic energy is imparted to the
leading structures.   Since this energy is proportional to the square of
the velocity and the area over which it is imparted is decreasing with
increasing velocity, the peak impact pressure may well follow a similar law.
This probably accounts for the difficulty of correlating resistance to rain
erosion of materials with their normally measured physical properties, since
molecular phenomena associated with solid surfaces in contact with water at
extremely high pressures are also involved.

A similar mechanism (repeated impacts at high pressure)is associated
with underwater cavitation.   Briefly, cavitation occurs when a liquid is
subjected to a tensile stress exceeding the rupture strength - a void forms
generally as a near spherical cavity.   Removal of the stress results in
rapid collapse of the cavity with the development of very high local
pressures.   It is not generally realised, however, that these pressures
can be of the order of 20,000 atmospheres[1], and bear little relation to
the initial tensile stress.

With liquids containing dissolved gases, a stress, or rather negative
pressure of little more than one atmosphere is required to cause cavitation.
Due to coalescence and diffusion of neighbouring gas nuclei, these cavities
generally contain appreciable quantities of gas which results in their
incomplete collapse with the formation of a permanent bubble in the liquid
and a considerable reduction in the peak pressure.   In the absence of
dissolved gas, cavitation is initiated at permanent "faults" in the liquid.
These are referred to in the work of Eyring[2], Furth[3], and others, who
postulate the existence of voids or holes in the liquid structure analogous
to the lattice defects in solid crystals.   A higher negative pressure is
required, about 7-12 atmospheres, to cause cavitation, and the subsequent
collapse is more rapid and complete, and gives rise to the very high
pressures referred to above.

The destructive action of cavitation was first recorded by Reynolds[4]
in 1894, with water flowing through a tube with a narrow constriction, and
later was found to cause virtual destruction of the propellors of the
Lusitania and Mauretania after running a few hours at full power.   Exten-
sive studies were carried out during the First World War and more recently
with the development of Venturi systems, large turbines, and other hydraulic
machinery, where high negative pressures can exist.

It is also of interest to note that the resistance of all materials
studied showed that their relative resistance to cavitation erosion could
not be predicted from their known physical properties.

In the application to the aircraft problem, it was considered that the
erosion may have been partly due to the direct action of cavitation, arising
from intense high frequency vibration on the leading edges of the aircraft
in the vicinity of the jet engines.   In flying through rain a permanent
film of water forms in those regions in which cavitation could occur.   From
structural considerations this now seems unlikely although owing to the
difficulties involved there is yet no direct experimental evidence to the
contrary.

Regarding the mechanism of a single drop impact recently investigated
by Dr. Engel it would appear that assuming physical wetting of the surface,
the high lateral velocity in the upper layer of water could easily produce
the negative pressure required for cavitation with the resulting annular
pitting observed.   It is possible that at speeds in the region of Mach 2
this effect is obscured by the more destructive shearing action arising
from the deformation of the solid surface.

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From these considerations it seemed likely that measurement of the resistance to cavitation erosion of materials in the laboratory could be correlated to some degree with the R.A.E. whirling arm erosion tests.

Various methods of producing cavitation were investigated involving the use of magnetostrictive rods and tubes, quartz crystals and barium titanate transducers. Owing to the small cavity size and the resulting low pressure on collapse, no signs of erosion were observed at frequencies in the region 250 Kc/s - 2.5 Mc/s, even with focussing devices. Severe erosion was found to occur in the region 10-30Kc/s and most of the work has been carried out just above the audible limit, for convenience.

The method finally adopted was similar to that of Gaines[5], who produced cavitation by the use of a magnetostrictive nickel rod immersed in water.

Early experiments were carried out with the rod and exciting coil totally immersed and specimens placed near the end of the vibrating rod in the region of the cavitation cloud. Perspex, aluminium, steel, polythene and glass were irradiated for a fixed time and the visible degree of erosion correlated with earlier American results on their propellor tests. It was difficult, however, to obtain quantitative results by this method owing to the low rate of erosion and critical nature of the distance between the transducer and specimen.

By mechanically attaching small specimens to the end of the rod it was found that weight losses could be determined and the factors governing the rate of erosion were investigated. The erosion rate varied considerably with variation of power supplied to the transducer and the strength of the polarising field. The temperature of the water was important since the rate of erosion reached a maximum at approximately $40^\circ C$, while at $80^\circ C$ no perceptible erosion was obtained, owing to the pressure of water vapour in the cavity.

Using distilled water that had previously been boiled to remove dissolved air, rapid erosion was obtained while approximately half this rate was obtained with ordinary tap water.

Initially the acoustic power fed to the liquid was measured calorimetrically before each experiment and the current fed to the exciting coils maintained at a constant value throughout. The power levels employed were of the order of 4-5 watts, resulting in a weight loss for aluminium of approximately 2 mg/hour. Results by this method were very variable, being well outside the accuracy of weighing. Attempts were made to monitor the cavitation by observing the amplitude of the harmonic content by means of a titanate disc immersed in the liquid, without much success.

A successful method of monitoring was eventually developed, depending on the shock excitation of a thin titanate disc placed in the liquid. The output of this disc with a natural frequency of 2 Mc/s is fed via a rejection filter tuned to the magnetostrictive oscillator frequency, to an amplifier tuned to 2 Mc/s. The output of this is integrated, rectified and fed to a milliammeter. By maintaining a constant reading on this instrument it is possible to obtain reproducibility within the accuracy of the balance, 0.1 mg.

The test-rig and layout finally developed are shown in Figs.20 and 21. A commercial signal generator and amplifier are used for exciting the transducer coils. The polarising field is obtained from a permanent magnet suitably shunted to give the optimum field. With this arrangement, the

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field is practically uniform along the length of the rod.   The transducer itself is a nickel tube with brazed end pieces suitably threaded to take various specimens.   The tube is supported at the mid-point by means of a brazed flange approximately 0.5 mm thick.   This is firmly fixed to the bracket holding the coil assembly which, in turn, is rigidly bolted to the magnet.   The coils and rod are placed in a Perspex tank through which water is rapidly circulated from a thermostatically controlled reservoir.   The water is previously boiled and the gas content maintained at a low level by means of a piezoelectric disc fed from a separate oscillator and vibrating at 1.5 Mc/s.

Air bubbles liberated from this are prevented from reaching the Perspex tank by means of a simple trap on the inlet side.

The specimens are carefully dried and weighed and screwed into position.   By using a small rubber padded vice designed for the purpose, the specimens are held sufficiently rigidly to the rod and no weight change is observed on repeatedly removing and replacing the specimens.

A 2 Mc/s disc mounted in the wall of the measuring tank is used to monitor the cavitation energy.   Throughout a test run the water temperature is maintained at $38\,^{\circ}C$ within $0.5\,^{\circ}C$.   This arrangement provides automatic cooling of the coils and nickel tube.

Perspex and a number of metals and alloys have been tested with this apparatus and listed in order of their relative resistance to cavitation erosion (Fig.22).   As yet no quantitative method is available for the whirling arm tests whereby the correlation between the two methods may be checked.

Elastomeric compounds have so far been neglected since, as in the case of the whirling arm tests, the rate of erosion is slow and initially in the form of pin holes rather than material removal.   In both methods this occurs at a later stage subsequent to the formation of blisters and destruction of the adhesive film by hydraulic action.

It is proposed in the immediate future to investigate a number of metal specimens coated with various grades of neoprene and paint finishes. Here the relative resistance will be determined by microscopic examination.

The general form of the erosion-time curve with the cavitation apparatus is linear for materials so far considered, although with prolonged exposure the rate tends to decrease because of the buffering action of trapped air in the deeper pits.   Extrapolation of the linear portion, however, indicates for certain materials a slower initial erosion or the existence of a definite skin effect.

The present technique of weighing will be extended in the near future by the use of a micro-balance which should improve the reproducibility of results by a factor of 20 or so and allow the quantitative measurement of the skin effect.

Other techniques investigated include surface examination by electron microscope and micro-comparator methods, and radio-active and colorimetric analysis.   Glass microscope slides were eroded for the electron microscope method.   A replica was formed by the use of ethyl cellulose subsequently shaded with vaporised chromium in the usual manner.   Fig.23 shows the outer fringes of an eroded area approximately 1 mm diameter after 15 minutes attack.   The regular nature of the individual pits is interesting and suggests that each cavity causes microscopic damage; the pits are approximately 100 millimicrons diameter × 100 millimicrons deep.   While this

the evidence is that the larger the molecule the less the erosion. This arose from the assumption that the rate of erosion bore some relation to the ability of the water molecule to penetrate the structure under high pressure. It was also thought, for the similar reasons that crystalline surfaces were more readily attacked at the grain boundaries. A porous anodic film was built up on an aluminium specimen and subsequently impregnated with molten polythene at 10,000 lb/sq in. and allowed to cool under pressure. All surface polythene was removed and the specimen subjected to cavitation. No erosion could be detected after 90 minutes although normally the anodic film would have disappeared after a few minutes running. However, after replacing the specimen and continuing the test for a further fifteen minutes or so, the oxide film separated completely from the aluminium.

This example is given merely to indicate the potential use of the apparatus and although owing to other commitments, the experiment was not followed up at the time, an investigation of this type can be rapidly carried out in the laboratory and may have promising results.

There are several factors present in the whirling arm erosion test which are not obviously reproduced in the cavitation equipment. The present apparatus may be compared to a fixed speed-constant rain density equipment, the corresponding values of which have not yet been determined. The effect of increasing speed can be obtained by raising the amplitude or decreasing the frequency, both of which would result in a larger cavity with higher pressure on collapse. An equivalent rain density variation could be obtained by the adoption of pulse operation of the transducer.

With the evidence so far acquired, however, in the absence of quantitative correlation, it seems that cavitation could well play a complementary role in the study of resistance to rain erosion.

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9 AMERICAN EXPERIENCE OF RAIN EROSION PROBLEMS AT SUBSONIC AND SUPERSONIC SPEEDS

E. W. RUSSELL, CHEMISTRY DEPT. R.A.E.

Introduction

This paper attempts to summarise the position regarding rain erosion in the U.S.A. as studied during a visit in March 1955 and a similar visit[1] in 1952.

Historically, difficulties were first experienced about 1945, and experimental studies[2,3] were commenced after erosion was observed on the laminated plastic radome of the B29. The tail fin of the F80 carried a suppressed aerial and the plastic leading edge was damaged. With increasing speeds the problem rapidly grew in importance; on F86A forward facing wing tips and fairings at the air intake were eroded, and it was recommended[4] that the use of plastics should be limited to electronic necessities. At 350 m.p.h. indicated airspeed, 8 plies were eroded through and some delamination occurred in 2-3 minutes. Actual failure of radar housings was also reported.

Test methods

The principal method of evaluating material or coatings for rain erosion resistance in subsonic flight is a simulated test, in which a test piece is moved at high velocity in falling water droplets of a standard size and concentration. Goodyear Aircraft Corporation and the Wright Air Development Centre (WADC) Materials Laboratory had early versions of such a rig which was further developed by the Cornell Aeronautical Laboratory[2,5-9]. The University of Cincinnati have a similar rig to that at Cornell; an attempt to go to supersonic speeds on a smaller rig at Louisville has proved unsuccessful[10].

Lockheed and North American[11] each developed tests in which pulsating or interrupted water jets impinged on rotating specimens. These and other abrasion methods failed to rate materials in accord with service experience[2,12,13] and have all been abandoned. In particular Neoprene showed up poorly in these tests. Preliminary work was also undertaken at Cornell on a cavitation method, in which the test piece was vibrated under water by means of a magnetostrictive transducer. The matter was not pursued as far as they wished, and has been in abeyance since.

Cornell attempted[8] to fire single drops of water at plastic specimens using a shot gun with reduced charges to project a carrier with the water droplet at a stop, beyond which the water carried on to hit the test piece. Work has discontinued because of doubts as to the cause of the damage obtained.

The Applied Physics Laboratory (APL) of Johns Hopkins University are experimenting with a droplet firing gun. Photographs indicate that so far only subsonic speeds have been achieved; it is uncertain how the drop proceeds. They plan to shoot into an evacuated space in future work to avoid break-up of the drop.

Convair[14] have made an assessment of possible test methods and concluded that whilst highly desirable, a method of water droplet acceleration presents serious development problems. For the ultra-sonic case, 20, 30 and 57 mm projectiles are being fired at speeds of M = 2-2.6 through artificial rain. In one form of apparatus in a flight of 150 ft an average of 3 drops of water are hit. The projectile is then trapped and arrested by compressing air in a tube in front of it. A bung in the end of the tube is arranged to drop out just as the shell comes to rest. In another case the head of the free flying projectile is separated and arrested by parachute. Multiple firings are made if desired. Since they are working on a desert site water is recirculated for the rain; drop sizes are rather scattered. Test pieces have not been preconditioned to simulate kinetic heating.

Rocket motored sled tests at M = 2 are planned at Edwards Air Force Base accelerating over 3800 ft and maintaining speed for 1000 ft. A

variety of test pieces such as a ceramic radome are to be included. A radome 106 in. long, 21° included angle and 31.6 in. diameter at the base with a 2 in. radius nose, will be fitted with a series of light alloy wings as catchers to determine the mass at various stations. By separate calibration of damage against drop size it is hoped to study droplet survival through the attached shock wave.

A.P.L. are also planning a series of missile firings. The first, known as Pinocchio, is a wooden non-stabilised missile with a conical nose of 30° included angle. It bears a Teflon tip as an erosion standard and 12 stations for test pieces. The barrel is about 8 in. diameter covered with polyester glass tape. Erosion of the unprotected wood is neglected in firings through natural rain; recovery is by floating on water. Test pieces of glass, Mycalex, ceramics etc. are proposed. A 57 mm stabilised projectile for firing through natural rain will consist of the same materials with the frequent inclusion of Teflon samples as standards. In parallel Cornell will test the same materials using samples on the rotating arm arranged for normal impact.

Basic studies

Before outlining the results obtained a brief summary of the more basic investigations[15] made by Dr. Olive Engel at the National Bureau of Standards is necessary. She first observed the behaviour of drops striking a flat solid surface at relatively low velocities by high speed photography. During the collision the rear of the drop retained its shape whilst the remainder flowed radially outwards. By introducing a tiny crystal of potassium dichromate into the bottom of a drop the flow of water was mapped on a filter paper and developed with starch-iodide. This showed that the water which struck first travelled the greatest distance in a series of radial channels. From the photographs it was evident that the horizontal velocity was much greater than the impact velocity.

Considering a single drop Dr. Engel assumes that compressional wavelets are initiated at the points of contact between the effective striking surface and the droplet. At some instant after the first impact a new wavelet will be initiated which will reinforce that formed first. Thus there will be a circle of maximum pressure. Expressions were derived for the thickness of the disc in radial flow, for the diameter of the circle mentioned and for the mean pressure within it. At 600 m.p.h. this is of the order 30,000 lb/sq in. and a radial velocity of 1300 m.p.h. was calculated. In the Cornell tests eroded holes 2-5 times that of the calculated circle of maximum pressure have been measured. The pressure is independent of drop size but the diameter of the circle is a function of drop size.

For an understanding of the erosion mechanism two properties of the drop are assumed: (1) that it behaves as a hard sphere and (2) that it retains the property of flow. Impacting Plexiglas with hard steel spheres gave crazing patterns corresponding to the tensile forces set up when a sphere is compressed into a cavity, assuming cracks to be produced at right angles to the imposed stress. Using lead pellets which have the additional property of flow the well defined circular crack was absent. Material was broken out along the tangential cracks in the direction away from the centre, and in some cases a sub-surface shear crack was observed. A comparison of such impacts with high speed short time erosion in the Cornell rig indicated that the mechanism was the same differing only in degree. Summarising, a cup-shaped depression in the surface of a brittle plastic is produced by the primary impact, with the formation of cracks which are widened and broken up by the radially flowing liquid. A large drop produces not only

a larger circle of damage but contains more water for the second stage of erosion by side wash.

Dr. Engel discusses the erosion of metals as a two stage process of initiation and progression. Residual surface imperfections may act as nuclei, any pit serving as a pressure raiser (c.f. the ear trumpet) sufficiently to permit damage within it. The scouring action of the side wash may induce hollows capable of acting similarly. A cavitation mechanism has been suggested as an alternative method of producing the initial roughening. The outward momentum of the water after impact may reduce the pressure locally below the vapour pressure and permit a cavity to form, which may collapse with damage to the surface. After considerable experiment Dr. Engel no longer thinks this phenomenon plays any important part in the mechanism of rain erosion. In her view the maximum resistance to erosion will be found in the hardest metals, glass or ceramics which do not depress under the primary impact, combined with high shear strength to resist radial flow. These properties should be considered at the high rates of stressing characteristic of droplet impact. Rubberlike materials can be deformed under stress and will recover if sufficient time is permitted before the next strike. Highly resilient rubbers recover quickly, but at sufficiently high rates of compression all rubbers behave as hard elastic solids and will then erode like rigid low tensile strength materials. Good stretching fatigue resistance is needed; damage accrues when the surface exhibits permanent set or insufficiently rapid recovery.

Convair are running tests using mercury or a low melting alloy instead of water as the impacting fluid. In aluminium alloy at 400 m.p.h. similar sized depressions were observed as those obtained with water at $M = 2$. The formation of new alloys and corrosion were observed immediately after the metal impact and the physical form of the erosion differed from that with water. The view was expressed at Cornell that other phenomena mask the main effect; the balance between impact and side wash damage may be different.

Results

Subsonic speeds

An outline of the principal results will be given dealing first with the subsonic case as tested at Cornell.

The quantitative measurement of erosion has proved a matter of the utmost difficulty, but in a number of cases Cornell have been able to pick out the part of 50 per cent erosion microscopically along the edge of a test piece after a given period of running. Making use of the velocity gradient along the test piece they have been able to calculate the actual velocity for this degree of erosion. From the slope of the log plot of time against velocity a variation of erosion rate with the 6-8th power of velocity has been deduced. Because of the subjective character of the observations the results need to be treated with some reserve. An extrapolation to higher velocities and possibly the application of the law to other types of material would be dangerous. Erosion is nevertheless obviously very sensitive to impact velocity.

It was not possible on the original apparatus to vary drop size independently of the rainfall, but by the use of multiple jets limited tests have been made. For a constant drop size of 1.9 mm, more impacts were required for a given amount of damage at 3 in./h than with 1 in./h rainfall. This effect was attributed to interference between the mist produced at the higher rainfall with the impacting drops. For a constant 3 in./h rainfall

2.5 mm drops were 3-4 times as destructive as 1.9 mm drops. At the lower velocities initiation is seen as a fatigue process; at higher speeds each impact produces damage.

The effect of temperature on erosion has only been studied within narrow limits and no significant variations were observed.

On flat plastic surfaces an angle of 60° between the specimen and the path of the drop was critical. Erosion was considerably greater above that value than below. At 15° negligible erosion was obtained. These early results at 250 m.p.h. have been substantially confirmed for the higher subsonic cases.

Turning now to materials, it can immediately be stated that all the rigid brittle resins used in structural plastics are rapidly eroded under the standard conditions of test - 500 m.p.h. in 1 in./h rainfall of 1.9 mm drops. All results to be given will refer to these conditions unless otherwise stated. Only minor improvements are achieved by filling the resin. Laminates with reinforcing fibres are worse than the cast resins especially where the resin coat on the surface is thin. Improved laminates fall far short of a useful life so that the development of an erosion resistant coating of suitable dielectric properties became inevitable.

An extensive development programme led to the application of the 2 standard Neoprenes, Gates Engineering Gaco N-79 and Goodyear 23-56, used in conjunction with the primer Bostik 1007. Space does not permit mention of the details of the many plastic and elastomeric coating systems that have been investigated in this programme.

The ageing characteristics of Neoprene have been open to suspicion and somewhat variable results reported. The latest given at Cornell were a 10 per cent drop in properties after 1 year's ageing in Florida, Panama or Alaska. There was some surface crazing and cracking and the Gaco exhibited some chalking.

Cornell have made a detailed investigation of the effect of Neoprene thickness and have found that

$$t = k \, d^2$$

where t is the erosion time, d the thickness and k a constant of proportionality.

Comparative flight tests have been run on panels about 8 in. long contoured to the leading edge. The plane sustained severe buffetting. Results were much the same as those observed on the test equipment and not, as expected, much less severe.

Sandwich structures require adequate support of the skins by the core material for flight in rain. Foams are superior to honeycomb in this respect. The de-iced radomes previously described[1] have insufficient skin support even when skin thickness was increased from 0.010 in. to 0.030 in.

Early experiments on glass, in the form of hard glass tubes specially mounted, were promising. More recently test pieces of the normal aerofoil shape have been deeply pitted in much shorter times. Cornell are not yet satisfied with the results and have experienced difficulty with fracture of the test specimens. They hope to run tests on samples of varying temper.

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Tests on metals indicate that the light alloys are comparable in their resistance with Neoprene treated laminates. The appearance of the eroded surface is similar to that of sandblasting. Titanium and steels were highly resistance at 500-600 m.p.h., though it was noted that shotpeening, which presumably roughened the surface, markedly increased the erosion rate of steel. Conversely a high degree of polish can delay initiation. Three years ago it was stated that the leading edges of research aircraft were being Neoprene coated as a precaution against damage.

Supersonic speeds

Turning now to the supersonic case mention will first be made of the effect of kinetic heating as distinct from rain erosion.

Neoprene coatings were reasonably good at 500 m.p.h. after 2 hours heating at 375°F (190°C). Under these conditions the Bostik primer becomes thermoplastic and a new one is sought.

Of the materials with improved high temperature resistance, Kel-F, Poly FBA, Teflon and Terelene were poor when tested under standard conditions. Lactoprene after heating was one third as resistant as unheated Neoprene. White materials to withstand heat flash have been developed, including an experimental Neoprene and a Hypalon formulation. The latter is about one third as resistant as normal Neoprene. A Neoprene anti-static coating 23-57 has received WADC approval.

Convair found that at M = 2 a ceramic cone 3/32 in. nose radius was unaffected during $1\frac{1}{2}$ s flight. With a glass laminate nose $\frac{1}{8}$ in. thickness was penetrated right through in the same time. A 0.030 in. sintered stainless steel disc suffered the same fate either alone or with a thin ceramic coating. A neoprene coated test piece survived 8-10 s when the rain penetrated the coating and gouged the substrate from the point of impact to the base. One strike at M = 2.6 had a similar effect, removing the protective and leaving a complete score from front to rear on the light alloy head.

The question of drop survival when passing through an attached shock wave is considered an important one. A high density change may cause shattering of the drop. It was stated, however, that the University of Michigan have shown that the shock wave will not be effective in producing break-up or in preventing impact. The use of a metal tip to their radomes is favoured by AFL, Bell and Republic the last two on aircraft radomes in conjunction with a long pitotstatic probe, which will have an associated shock wave.

Conclusions

In conclusion it appears that there is at present no real answer to the supersonic case. The use of Neoprene is of some possible value in the missile case, but it has insufficient heat resistance for aircraft application unless flight times are very short. Much more information is required both on materials and design at these speeds; for example it is apparent that the angle of attack suitable for the subsonic case may no longer prove effective. The need for a laboratory test method remains: the M.E. Dept. gun or the projection of drops into a vacuum may yield a solution.

Acknowledgments

The author is indebted to Mr. F. G. Brown of Structures Dept., for the information he obtained at Convair, and to the authorities at WADC who facilitated the visits.

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9.1 Discussion

Prof. Tolansky

Might I ask one very pertinent question? When one obtains laws expressed as the 6th or 8th power of the velocity one expects that this is based on accurate measurement. I am very intrigued to know what is the definition of erosion and how it is measured? What is the unit and with what precision is it measured?

Mr. Russell

You will notice that I have said that it should be treated with reserve. The technique that Cornell applied was to examine the whole area with a microscope and subjectively to gauge the point at which 50 per cent of the area was covered with pits.

Prof. Tolansky

I would suggest that something much better than that could be developed. I would throw out a suggestion now that a measure of the amount of light scattered away from a roughened surface would be a precise measurement of the amount of erosion.

Mr. Russell

The Cornell work of course depends on the fact they have a velocity gradient along the test piece. At the moment on the R.A.E. rig we do not have that and we are therefore unable to make similar measurements.

Prof. Tolansky

An easy technique would be to have an integrating sphere, to move your sample along and to find with great precision the amount of light scattered away. The amount of light scattered is proportional to the amount of roughening and one could use a precision method.

Mr. H. G. Stubbs, The Plessey Co. Ltd. (Towcester)

Might I make a suggestion that with the very high pressures involved with drop impacts, there is a considerable amount of penetration below the surface and a light scattering technique would only observe the surface. Whereas one specimen may be eroded 10 times worse than another the result with this technique would not show this difference if the bulk of the erosion was under the surface.

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Prof. Tolansky

I was thinking of examination during the early stages of erosion.
Once it has really started I agree with you that this method would not
apply.

A speaker

Mr. Chairman, in the results summarised by the last speaker he
omitted any mention of work done at the Hughes Aircraft Co.   Has this
work stopped, is it still in progress or have we no report on it?

Dr. M.,G. Church, Mat.R.D.7 M.O.S.

I can add a little information on the work done at Hughes Aircraft.
When I discussed the subject with them recently their programme was based
on two forms of specimen, of which one is the same as the Convair small
conical nose which is attached to the head of the projectile and which
after passing through the rain belt, on a horizontal range of course, is
then ejected, arrested by parachute and collected for examination.   These
cones are 20 mm base diameter with various angles and they are being
tested in a range of materials with protective coatings and also with
small metal nose cones.   The second programme is based on the Falcon
missile which is being fired, again horizontally, over a 4 mile range, using
natural rain at Mach numbers of round about 2.6.   There again they are
using the first Falcon nose which is roughly hemispherical, with a 30 mm
skin of phenol formaldehyde resin-bonded glasscloth and sometimes backed
with a cast phenolic resin in order to examine pure erosion effects and
to guard against the actual collapse of the radome.   Their conclusions,
to summarise very briefly, are that the Neoprene is by no means satis-
factory and that as far as possible the use of a metal tip on a conical
radome so as to ensure a glancing attack by the raindrops on the non-
metallic part of the cone, is the best solution to the problem.   They
are also planning to use the sled at the Edwards Air Force Base which has
been described briefly and which does permit a selection of samples on a
test plate of up to 3 in. diameter to be carried.   Tests may be made at
speeds up to a Mach number of 2.   They have not so far carried out any
tests on that but we are hoping to get reports as they come through.

Dr. R. A. Roper, D. Napier and Son, Ltd.

I would like to ask Mr. Russell about the results on the Neoprene
coatings on the Cornell Rig.   Do we understand him to say that tests
were not borne out by experience in the air?

Mr. Russell

No, Sir, they are borne out by experience in the air.   It was the
jet impingement work of Lockheed and North American earlier which did not
bear out the results of flight work and for this reason this technique has
been abandoned.

Mr. R. J. Wareing, Marston Excelsior Ltd.

First of all in Mr. Russell's remarks about the thickness of the skin
which is necessary to support the neoprene coatings, I think he said an
increase from 0.010 to 0.030 in.   Does that foreshadow the fact that the
sandwich radome may become obsolete, and is the only answer a solid laminate
radome?   Secondly, did I understand from one of his remarks that there is
a requirement to protect against heat flash?

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SECRET

Mr. Russell

As regards the first question, Mr. Chairman, support will depend on the pitch of the heated air ducts, which is what they were on this particular radome. In the other direction the skins were unsupported. Thus these considerations apply in much less measure to standard honeycombs. The tendency I think is towards smaller cell-size honeycombs and in that case support would be adequate, at least for subsonic flight.

In regard to heat flash, experimentation is going ahead but there is nothing yet approved for the purpose. I think however they are within reasonable distance of a solution.

Mr. L. H. Mann, R. R. E., Malvern

I am dealing with that point about radome design in my talk later on.

Mr. J. H. Phillips, A.D.G.W, (G. & C.) M.O.S.

I would like to ask Dr. Church a question on his statement that a metal tip is preferred on a conical radome. Is this based on experimental evidence or theoretical considerations?

Dr. Church

On experimental evidence but I cannot supply any details of the results.

10   PROTECTIVE COATINGS TO RESIST RAIN EROSION
     J. MACKAY, CHEMISTRY DEPARTMENT, R.A.E.

At the Royal Aircraft Establishment many tests have been made on the erosion rig using, in the first instance, surplus aircraft propellers approximately 7 feet long, some made of wood and some of duralumin. The paint schemes and modifications of these schemes which were tried ranged from simple drying oil and nitrocellulose materials to heat and cold cured epoxy and polyurethane mixes. Specification and experimental formulations were submitted by some of the large paint manufacturers and by the Paint Research Station. Coating materials based on polyvinyl butyral, polyvinyl chloride, polyvinyl acetate and co-polymers, on natural rubber and synthetic rubbers including grades of Neoprene other than the grade used to meet the present specification (D.T.D.856) were also used. Of many other plastic materials only polyurethane sheet (Vulcollan) gave erosion resistance approaching that of the Neoprene coating.

The coating scheme based on Neoprene which gives by far the best erosion resistance, if properly applied, consists of the components listed in Appendix I. However practically no improvement in rain erosion resistance will be obtained unless two main requirements are met, viz. a good glass laminate moulding and a carefully applied Neoprene coating. This is amply illustrated by two typical photographs of glass laminate cylinders after a standard test on the whirling arm rig.

In Fig.24 a poor quality laminate made with heat cleaned cloth and having pin holes and voids has been coated with some difficulty to produce a good film of the approved Neoprene. The first effect of testing such protected laminates is a powdering and delamination of the glass cloth and resin under the neoprene film. This film, with practically no loss in thickness, eventually disrupts through, by breakdown in adhesion in times of 20 to 90 minutes.

In Fig.25 the test piece, a good quality void-free laminate made with vinyltrichlorosilane-treated cloth, has been coated with an equivalent thickness of the approved Neoprene. Here the only visible change is a gradual roughening of the surface until eventually the Neoprene coating is eroded right through to the laminate. The time for this to happen generally varies from $3\frac{1}{2}$ to $4\frac{1}{2}$ hours when using test pieces of this description.

Unless some care is taken to meet these two major requirements a complete glass laminate component may be condemned even without subjection to rain erosion (the flaws will show up in fair weather flying) and the high speed fighter or bomber aircraft is consequently grounded.

The method of application of the approved Neoprene scheme is described fairly thoroughly in Appendix I. At an early date experiments were made with a conventional drying oil type of primer and although it could be applied, under certain conditions, in combination with the Neoprene finish to give initially good protection yet the system failed after a period of storage through loss of adhesion between the Neoprene and the primer. It is therefore important that glass laminates should be free from all the usual paint type materials including fillers, stoppers and chalk or kaolin pastes.

The Appendix may be found to differ in minor details from the process specification (D.T.D.926) but this does not imply that the specification is in error as application according to its requirements will give excellent erosion resistance. However the further clarification which is given should simplify the application process quite considerably and, as far as possible, will be embodied in the specification together with any suitable improvements which manufacturers may now be able to add from their experience of the use of these Neoprene solutions. The complete operation of the application of the Neoprene scheme is one in which a certain amount of skill has to be acquired by trial and error, but with perseverance it will become no more difficult than obtaining a good smooth finish with orthodox paints.

There is a hint on drying times which may be helpful. If the finishing room (well ventilated by exhaust fans) is maintained at a slightly raised temperature, application of the materials will be facilitated quite considerably because of the more positive drying of each coat of finish. A temperature above 35°C must not be used because this appears to upset the uniform evaporation of the solvents and lo al concentrations give rise to surface bubbles and adhesion failures. The slightly raised temperature is very useful especially in spray application where a large number of coats have to be applied in one day.

It will be seen that stress is laid on the application of very thin coats both for the primer and for the finish. The number of coats of finish given should be taken as a minimum. It has been found that the quantity of thinners required often varies somewhat with the age of the materials and whether the container has previously been opened. Using a fresh batch of Neoprene cement and diluting with three volumes of thinners, 30 spray coats were required to give a 0.010 inch thick film. This gives a very fine finish but may cause a little difficulty in completion of the application in one day. To get a really good finish, the operator, when using brush application, should strive for a thickness of not more than 0.00075 inch per coat, and when using the spray gun, for not more than 0.0005 inch per coat. Recent tests have also shown that only the first coat of primer need be applied by brush and the remainder may then be completed by spray gun application.

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Effect of cure

The results of tests on rain erosion resistance of D.T.D.856 neoprene coating at various times after application are shown in Table I.

TABLE I

Sample	Time at 20°C before test	Thickness inches × 10³	Time to produce equivalent erosion	
A	16 hours	11	2 hours	15 minutes
B	38 hours	17	2 "	30 "
C	3 days	17	2 "	40 "
D	13 days	11	2 "	35 "
E	13 days	17	2 "	35 "
X	13 days	10	1 hour	5 minutes

Although the Neoprene coatings on the glass laminate sample test pieces A, B, C, D and E are not cured or vulcanised in the accepted sense of rubber vulcanisation (e.g. by tests on resistance to solvents) yet they dried completely tack free in 6 hours or less at 20°C and acquired quite considerable erosion resistance after 16 hours.

The coating on sample X is worthy of note. It was applied and dried in the same manner as the other coatings yet no accelerator (vulcanising agent) was used. It is therefore not quite clear what connection there is between vulcanisation and rain erosion resistance and further tests are being made. The glass laminate test pieces used in these experiments were of commercial quality and the resistance to rain erosion is therefore somewhat low.

Conditions affecting protective value

(a) Use of fillers, stoppers or paints.

Examples of the application of these materials to radomes either unwittingly or as a means of filling and smoothing minor imperfections have led to failures, sometimes of a delayed nature, to the external Neoprene coating.

(b) Insufficient preparation with garnet paper.

In several instances very low adhesion, as shown by easy stripping of the complete neoprene coating, has obviously been due to this cause. The present of parting agents and contamination after cleaning have also given trouble.

(c) Exceptionally thick priming coats.

Thick coats will bridge pin holes and minor imperfections of poor quality laminates. Numerous local failures by blistering and poor adhesion

have been attributed to this condition and the recommendations given in Appendix I for the application of the primer should be carefully observed. Delay before application of the Neoprene finish on top of the primer also causes adhesion failures.

The effect of other conditions on erosion resistance are amply illustrated by the results of whirling arm experiments on various qualities of glass laminate test pieces protected with the approved Neoprene coating. These results are shown in Table II and further comments are given in paragraphs d, e and f.

TABLE II

Description of sample	Thickness of Neoprene Inches × 10^3	Time to produce equivalent erosion
Loom-state glass cloth laminate	13	0 hours 45 minutes
Heat-cleaned glass cloth laminate	16	1 hour 20 "
Treated cloth but poor quality laminate (voids, pin holes etc.)	14	2 hours 15 "
Treated cloth but resin starved laminate	14	2 " 15 "
Good laminate made with treated cloth (V.T.S. finish)	14	4 " 0 "
Good laminate made with treated cloth (Garan finish)	17	4 " 25 "

(d) Surface flaws and voids

These defects make it difficult to obtain a good smooth finish during the application of the Neoprene coating and, on many occasions, have been found to be the cause of early failure in flight.

(e) Resin starved laminates

Blistering and generally poor adhesion of Neoprene coatings has been observed on glass laminate components in this category. Because of the porosity of such surfaces, solvents become entrapped under the Neoprene coating and cause blistering later. There is also poor adhesion of the primer due to deficiency of resin on the surface of the laminate. When erosion penetrates the Neoprene coating, delamination of layers of glass fabric is responsible for drastic spread of damage.

(f) Condition of glass fabric.

Table II shows that the best erosion resistance is obtained with Neoprene coatings applied to glass laminates made up with treated cloth. Such cloth gives better wetting of the fibres by the resin and so greatly assists the preparation of laminates free from voids.

APPENDIX I

The materials, approved to the latest issue of the specification, consist of the following components in separate containers:-

Primer - Bostik 9252   The B.B. Chemical Co. Ltd., Leicester.

Finish - Top Coat Base Cement Ref. 1801-C ⎫ The Goodyear Tyre &

       Accelerator Ref. 983-C ⎬ Rubber Co. Ltd.,

Thinners - Diluting Solvent Ref. 1803-C ⎭ Wolverhampton

Method of Application

Preparation of radomes

A preliminary point which requires attention in this connection is that if water soluble parting agents have been used in the moulding process the radome should be thoroughly washed with warm water and completely dried before rubbing down with garnet paper. To obtain good adhesion it is essential to ensure that a smooth even matt finish is obtained over the complete surface of the radome by using the grades of garnet paper recommended in the specification and in the correct order. A satisfactory result cannot be obtained either by the use of other abrasive papers or by the use of coarser grades of garnet paper. In the first case the papers rapidly become clogged with resin and in the second case a small number of deep and deleterious scratches are produced. After swarf and dust have been removed and the radome surface cleaned with toluene or other approved solvent there must be no surface contamination by handling etc.

Primer

In order to obtain the best possible adhesion to poor laminates it is essential that the primer should be sufficiently dilute to flow into pin holes and other small interstices. If the priming coat is too thick bridging of these imperfections occurs resulting in weak spots. With proper dilution, the application of two coats should give a total thickness of from 0.0005 inch to 0.00075 inch and should never exceed 0.001 inch.

A dilution of the Bostik primer, after stirring well, with two parts of toluene has been found satisfactory. The first coat should be applied fairly rapidly with a full brush followed by the use of a quick light stroke to remove any streaks which may form on the wet coating. Brushing on the second coat of primer often tends to remove slightly some of the first coat but it has been found that the second coat can be sprayed on satisfactorily and simultaneously prevents this minor difficulty. The spray gun must be held close to the work in order not to cause cob-webbing and a fairly low pressure of 20 to 30 lb/sq in. used for atomising.

At normal room temperature (not less than 18°C) each priming coat dries in 5 to 10 minutes but not less than 20 minutes or more than 60 minutes should elapse between completion of the application of the primer and commencement of the application of the first coat of finish.

Finish

The top coat base cement and the accelerator should be thoroughly mixed in the proportions recommended by the manufacturer and diluted to the desired consistency for either brush or spray application. For brush

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application toluene is suitable but for spray application the blend of thinners supplied by the manufacturer must be used.

(a) Brush application

    To obtain a smooth even coating free from pinholes and occluded bubbles a thickness of 0.00075 inch per coat should be aimed for i.e. the application of 13 to 14 coats to give the required optimum total thickness of 0.010 inch. This has been obtained by taking 1 part of toluene, 1 part of top coat base cement and the required quantity of accelerator and stirring together until homogeneous.

(b) Spray application

    With suitable dilution it is possible to apply the complete coating of finish by spray. This dilution should give a thickness of 0.0005 inch to 0.00075 inch per coat i.e. the application of about 20 coats to give the optimum total thickness of 0.010 inch. This has been obtained by taking 3 parts of the thinners supplied by the manufacturer, 1 part of top coat base cement and the required quantity of accelerator and stirring together until homogeneous. Once again the spray gun must be held fairly close to the work and with 20 to 30 lb/sq in. atomising pressure a uniform wet, but not heavy, coat of finish applied.

(c) Drying time

    With these procedures for brush or spray application a drying time of not less than 10 minutes or more than 60 minutes for each coat of finish has been found satisfactory provided the room temperature does not drop below 18°C.

Note The proportions for dilution of the primer and finish for either brush or spray application are given as a guide only, as coating is dependent on the individual operator, the equipment and the materials. The main requirement is that the thickness of each coat and consequently the number of coats applied, should be as near as possible to that recommended.

10.1 Discussion

Mr. R. J. Wareing, Marston Excelsior

    I am very interested in Mr. Mackay's last few tables showing the effects of curing time on the erosion properties of the Neoprene. At the present time the specification requirement is that the radome shall stand in a dust-free atmosphere for 7 days. At various times that specification has been modified to 14 days and 28 days. From what you have said the coating is not only fully erosion resistant after 16 hours but it seems also that the requirement to stand in a dust-free atmosphere for such a length of time is unreasonable. Radomes are very big things and to stand radomes around in the production shop for a fortnight is very hard on the manufacturers.

Mr. Mackay

    These results were only obtained recently and consequently the specification has not been amended at the present time. The main purpose of the investigation however was to show that although the Neoprene may not be fully vulcanised after 7 days yet this was ample time for the development of satisfactory rain erosion resistance. It was Neoprene coatings which were unsatisfactory for other reasons that gave rise to suggestions that the curing time should be extended. I think it is most important that the finished radomes do stand in a dust-free atmosphere as the presence of even

minute particles on the surface of the coating provide nuclei on which rain erosion may start.

Mr. A. Cooper, Expanded Rubber Co.

I was surprised to know the slight difference there appeared to be between vulcanised and unvulcanised coatings. I would have expected a far greater difference. Does this not indicate that what is required is a soft undercoat? Has that been tried at all? Has a far softer compound next to the glass laminate and then finished off with an outer coat of fully vulcanised Neoprene been used?

Mr. Mackay

I think this is a very worthwhile suggestion but I cannot recall any tests which have been done with a softer undercoat. It is known that there must be a good strong bond between the Neoprene finish and the glass laminate. The softer compound would probably allow the Neoprene to be distorted and finally to be ruptured under the repeated high speed impacts with rain drops.

Mr. J. W. Denson, Goodyear Tyre and Rubber Co. (G.B.) Ltd

Before we get the idea that Neoprene does not require vulcanising I think we will have to do a lot more work and I think we should study these figures a little more closely. It will be seen that the unvulcanised coating gave roughly half the resistance of the vulcanised one and yet it stood for 13 days which was several times longer than the 16 hour one, so that vulcanising has a considerable effect. Even where there is no accelerator added a certain amount of structure formation takes place, and the 7 days which is the present requirement while it is more than is necessary, is a good overall, foolproof time and it has been stated that in emergencies it can be used in a matter of 2 or 3 days. We must remember the difference between making and covering radomes in the laboratory under absolutely perfect conditions and covering them in commercial practice where all sorts of things may go wrong. Consequently one must have this factor of safety, and I think that that is a thing we must remember.

Mr. P. L. Britton, Armstrong Whitworth Ltd.

Is there any relation at all between the thickness of the Neoprene and its life? Is the 0.010 inch as required in the specification so critical?

Mr. Russell

In my paper this morning I described Cornell work in which the time to erode was given as being proportional to the square of the thickness. I am afraid that our friends at R.R.E. will not allow us to exceed the thickness required by the specification.

Mr. G. A. D. Shaw, Vickers Armstrong Ltd. (Weybridge)

Can we expand the subject to include the case of dielectric covers in leading edges where the critical radiation at centimetric wavebands is not present?

Dr. Megson

Mr. Mann will probably cover this in the next paper.

11   RADOME DESIGN WITH RESPECT TO ELECTRICAL AND RAIN RESISTANCE PROPERTIES
      L. H. MANN, RADAR RESEARCH ESTABLISHMENT.

The modern radome problem

The advent of the supersonic aircraft has presented many serious problems in the field of radome design, and has at the same time emphasized the urgent need for improved techniques of radome manufacture if the mechanical and electrical requirements of the radome designer are to be met. Concurrently with the demand for design and construction suitable for high speed aircraft has come a complexity of the radar system which requires more exacting electrical performance from the radome itself, for it should be clearly understood at the outset that from the electrical aspect, the radome is part of the aerial system with which it is associated, and that any inadequacies, whether of design or manufacture, will promote distortions of the radiation diagram on account of reflection losses in the radome, diffraction effects at discontinuities, and the effect of variation of path length as the radiation traverses the radome transparency. To these effects must be added that of true absorption loss, with its effect on transmitted and received power, and consequent loss of range. Current radome materials are however moderately good dielectrics, and although absorption loss is always undesirable, its elimination is not the dominant question, and the problems of modern radome design still centre on the elimination or reduction of reflection, diffraction and path length errors.

Side by side with the satisfaction of these electrical requirements, a number of new mechanical problems arise in the supersonic aircraft radome. Chief among these are (1) erosion resistance of the structure at the high speeds involved, and (2) the demand for materials of satisfactory and consistent mechanical and electrical properties up to temperatures of 200°C or more, as the radome, like all other parts of the aircraft structure, will be subject to the effect of kinetic heating.

Trends in radome design

Future trends in aircraft radome development appear to fall into two main categories, i.e.,

(1)   Conical or near conical structures for nose installation, of total cone angle 30° or less.

(2)   Long windows, of length up to 50 feet, for sideways looking radars for reconnaissance purposes.

The favoured radio frequency is still in the X Band range, but there is likely interest in Q Band for radomes in both categories. There appears to be little future interest in S Band and lower frequencies, and this note will therefore confine itself to the problem of design in the X and Q Bands.

Choice of radome design

In any new problems there are a variety of basic radome designs which are on a first analysis suitable for meeting the electrical requirements of low reflection and freedom from beam distortion.

These are (1) a homogeneous dielectric, of effective thickness equal to one half wavelength

(2) a thin walled single sandwich, the walls being spaced one quarter wavelength by an expanded core of low dielectric constant

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(3) a thick walled single sandwich, similar to (2), but whose
walls are effectively those of the comparatively simple
design of (1)

(4) a thin walled double sandwich, which is most simply conceived
of as two single sandwiches of the second design in intimate
contact

(5) a 'bloomed layer' radome, consisting essentially of design
(1) with reflection matching layers, approximately a quarter
wavelength thick, on each surface.

Each of these five fundamental types has its own intrinsic advantages and
disadvantages, which may briefly be summarised as follows:-

(a)   Homogeneous dielectric radome

This has the great advantage from the electrical standpoint that the
reflectionless half wavelength thickness (which is a function of the angle
of incidence of the radiation) is theoretically the same for all polarisa-
tions of the radiation.   This is of particular importance for radomes where
the incidence angle is high, or those in which the range of angles in scan-
ning covers most of the available range between 0° and 90°, and circular
polarised systems naturally must favour this type.   Its chief disadvantage,
as compared with the sandwich types, is the relatively large weight penalty
and often the time of construction.

(b)   Thin walled single sandwich radome

The reflectionless thickness changes much more rapidly than with
radomes of the previous type, and for a radome of high electrical performance
(which we will define as one in which no incident ray shall have a reflec-
tion coefficient in power of more than 2%) it is found that the construction
may be used only if the angles of incidence do not much exceed 60°.   It
therefore remains, where it has always stood, an excellent type of design
for the near normal incidence radome.

(c)   Thick walled single sandwich radome

This is an attempt to reduce the reflections of the skins of the
sandwich by a matching technique, and it is an effective measure if angles
of incidence are not high.   It does nothing however, to solve the high
incidence problem, and at the same time because of the greater thicknesses
involved, radome aberration errors are more serious.   The weight penalty
makes it unattractive for an X Band application;   it is however a possible
design at Q Band.

(d)   Double sandwich radome

This design arose naturally from the single sandwich in an attempt to
improve the acceptable range of angle of incidence, and theoretically
the design is very effective if the polarisation is maintained perpendicular
to the plane of incidence, when angles up to 75° may be covered.   It is
less effective for the orthogonal polarisation, so that if in a given design
all polarisations must be covered, the limiting angle of incidence must
probably be set at about 70°.

(e)   Bloomed layer radome

This radome employs the well known optical technique of surface
matching layers a quarter wavelength thick and having a dielectric constant

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the geometric mean between that of the core material and that of free space.
An advantage of the construction is that, unlike the sandwich types, it has
a completely non-critical core thickness, and it is also very well matched
provided that the range of angle of incidence is not too large.   An obvious
disadvantage is its relatively great weight (it must be heavier than a
corresponding construction of type (a)), and it is not likely to be favoured
unless great mechanical strength is at a premium.

Materials

It is true to say that no completely satisfactory substitute has been
found for woven glass cloth, laminated in layers with polyester resin, as a
basic radome material.   Much, however, needs to be done to improve tech-
niques of manufacture in order to improve consistency of the final product.
For a fine angled conical radome, the final structure for fully efficient
operation would require a dielectric constant consistent to 1 per cent and
this means that presence of voids in the laminate, and conversely the
presence of resin accretions, are not to be tolerated.   All the emphasis
in the forward looking requirements must be on material consistency, both
initially and during life and it is to this end that the use is recommended
of low alkali cloth, pre-treated by the V.T.S. or Garan processes, and the
use of resins (such as the Bakelite SR 17449) of good characteristics up to
temperatures of 150°C or perhaps higher.   Much however remains to be done
to evaluate possible resins for consistency of dielectric constant and loss
up to these elevated temperatures, and it should at the same time be
remembered that if the requirement for high temperature operation is to be
extended, these newer polyester resins (even now rather marginal in
mechanical performance) will have to be replaced.   Here the use of sili-
cones has been suggested but the problem of laminating with these materials
to the necessary conditions of consistency has not yet been tackled in this
country.

Manufacturing techniques

The conical nose radome has already been mentioned as a problem for
the aircraft of the future.   If the cone angle is not to exceed 30°, angles
of incidence will be at least 75° in the direction of forward view for all
rays from the contained aerial system.   If, at the same time there is a
requirement for wide angle scanning, and the absence of radome reflections
which can lead to spurious signal returns, then from what has been said
earlier it appears that the favoured design for an X Band radome would be
a homogeneous solid laminate whose wall thickness would be suitably tapered
towards the rear in order to maintain the reflectionless half wavelength
condition under all conditions of incidence.   Tolerances on laminate thick-
ness will be tight - particularly in the nose region - and of the order of
plus or minus 0.004 in.   In the nose itself the dielectric material will
be replaced by a metal plug, shaped to correct external contour, in order to
alleviate erosion at the most forward point, and from electrical considera-
tion the base diameter of the plug should not exceed one twentieth of the
mirror aperture.   For the achievement of this type of radome, positive
male and female moulding tools appear to be essential.   Lay up of the
laminate (on, say, the male mould) should ensure the complete absence of cloth
overlaps and all precautions should be taken to see that the laminate is
void free.   The use of a transparent flexible bag with vacuum pressure, as
an intermediate stage before the application of the female mould and the
curing cycle is probably essential if all voids in the final structure are
to be eliminated.

Long windows for sideways looking radars are an easier problem, and
the electrical characteristics would be readily met by a single sandwich

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construction, either thin walled (for X Band) or thick walled (for Q Band).
In order to satisfy the requirement for operation at high temperature a
glass honeycomb core is essential. There are still the same problems of
making skins homogeneous and of consistent electrical thickness, and the
bond to the honeycomb core must be carefully controlled if the resulting
sandwich is to be fully satisfactory electrically. Also in a Q Band
radome, the size of the honeycomb mesh and the wall thickness will need
careful appraisal.

Erosion problems

It will be seen that the types of radome so far discussed will have
their exposed dielectric surfaces very oblique to the line of impact of the
rain drops. On the basis of existing knowledge at subsonic speeds (where
it has been found that erosion is imperceptible with angles of attack of
15° or less) it might be thought that the problem was alleviated, but too
little is at present known of the conditions of erosion at supersonic
speeds to allow for any present confidence. In particular, in the conical
radome, it might be expected that erosion would be severe at the junction
between the metal nose cap and the radome structure proper, and information
on the extent of this, and steps to be taken to minimise erosion, is
urgently needed.

Where an erosion resistant layer is required, it will have to be of
controlled thickness and to be allowed for electrically in the radome
design. It is well known that Neoprene, as at present in use, is applied
to a thickness of 0.010 inch and a plus and minus tolerance of 0.001 in.
is asked for, and seldom achieved, on existing techniques. Control of
Neoprene application to within specified limits, will be imperative in
fine angled conical radomes for the future.

From the electrical standpoint, Neoprene is a reasonably satisfactory
material, as its dielectric constant is not far removed from that of the
glass cloth laminate to which it is applied, and a straightforward
compensation by removing an equivalent thickness of glass cloth, is
reasonably effective electrically over a wide range of angles of incidence.
If however, alternative resists were proposed, whose dielectric constants
were (say) similar to those of polythene or P.T.F.E., and consequently
about half that of the underlying laminate, electrical compensation for
the resist layer would not be satisfactory over a wide range of incident
angles, and the performance of a radome would suffer unless the laminate
could be brought into closer electrical compatibility with the resist
itself. This would effectively mean that a search would have to be made
for radome materials of low dielectric constant, and here a word of warning
is necessary. While reduction of dielectric constant from (say) the
value of 4 of existing laminates will always assist in reducing reflections,
or alternatively in widening thickness tolerances, radome aberration errors
consequent upon path length variations, tend to worsen towards a pessimum
value before declining to zero for the dielectric constant of free space.
In fact, for a cone of total angle 30°, the theoretical pessimum value of
dielectric constant is 2 on consideration of primary aberration errors,
(i.e. ignoring the effect of multiple reflections) and it is worth
remarking that this value is very close to the dielectric constant of
P.T.F.E. It should however be realised that this theoretical analysis
ignores the effect of mismatch, which may tend to dominate as the dielectric
constant is increased, and the theoretical estimate of aberration is thus
a complicated problem which probably needs individual assessment for each
chosen radome shape. But as a general guiding principle, and taking all
factors of electrical design into consideration it does not seem wise to
contemplate a reduction of dielectric constant of homogeneous dielectric
radomes below a value of 3.0.

11.1 Discussion

Mr. S. C. Dunn, The English Electric Co.

Mr. Gompertz, of the English Electric Company, has put forward a theory of radome aberration based on the insertion phase shift in a nominally $\lambda/2$ thick wall. This theory suggests that aberration will decrease significantly if the dielectric constant is reduced. Experiments with a polythene radome did not realise this expectation so a radome was made with a phenolic resin foamed to a dielectric constant of approximately 1.2. The aberration records looked very like those obtained for other radomes, but the following points must be taken into consideration:-

1 So as to be strong enough the wall was in fact λ thick.

2 An appreciable number of bubbles were of diameter greater than 0.1λ.

The radome, which was 64 in. long with a base diameter of 18 in. and circular arc profile, was foamed between an accurate male and a rough female mould. The female mould was then removed and the shape accurately machined.

Mr. Mann

I am not quite sure what the aberration is affected by.

Mr. Dunn

By reducing K from values between 3 and 4 to values fairly near unity. I would like to ask a question too. Has the effect of putting on layers of Neoprene been measured as regards the actual value of aberration?

Mr. Mann

It probably has been measured incidentally but I cannot quote any figures to you.

Mr. Goacher

I should like to state that although Mr. Mann was referring to aircraft radomes we have been making guided weapons radomes of silicone resins for some time, and there are one or two points about them that it would probably be as well to mention. Firstly, although I do not know if it has been tested I should imagine that the resistance of a silicone laminate to erosion would be very poor because as resins go, at room temperature anyway, they are not very good. They are quite porous and full of voids, even in a good silicone radome. Secondly, Neoprene is not much good on silicone radomes as it does not adhere very well to the silicone laminate and it is possible to apply a very good protective coating of Neoprene and peel it off by hand. Silicone rubber can be made to stick to these laminates but I do not know what the erosion resistance of silicone rubber is likely to be.

Mr. Mann

Would you say that you have studied the manufacturing technique sufficiently on the silicone resins because I am interested to hear what you have done, as in most of these problems the solution comes out after a very considerable time? How long have you been working on this problem?

Mr. Goacher

About 2 years. We must have made about 100 radomes or so. We started off with vacuum moulding and we are now using matched metal moulds. We are producing a reasonable-looking radome, which has been mechanically tested for the necessary strength and I believe that it has very good aberration characteristics and very low loss at high temperatures. Its electrical characteristics do not change much with temperature. We could probably improve on them quite a lot if the shape of the radome, which is at present hemispherical, could be changed.

Mr. Russell

I should like to ask Mr. Goacher to what temperature he has tested in the high temperature case, because silicone laminates are under severe suspicion of being thermoplastic at high temperatures.

Mr. Goacher

Yes, that is true, they are slightly thermoplastic, but so far as we have been able to find on rather limited mechanical testing, the strength of a silicone radome, or rather of a piece cut from a silicone radome, crossed over at about 200°C with the strength of a Bakelite polyester 17449 radome. At 250°C in spite of the slight thermoplasticity, which is reduced by a very long cure, the silicone laminate is superior to the polyester.

Mr. Russell

I was thinking actually of temperatures somewhat greater than that. In discussion with Goodyear Aviation they mentioned the sagging of radomes at 700°F. (that is 370°C). As for the rain erosion resistance of silicone rubber, it is shocking.

Mr. Goacher

I should mention perhaps that we are not banking on silicone rubbers to prevent rain erosion. We have assumed that laminate just won't stand up to it and we have made provision for another method of protection which might be of interest. It is a glass cap which fits over the nose of the radome and is shattered by a small explosive pellet immediately before firing the missile. We think that the glass cap will certainly suffice to prevent erosion during carry and during climbing to altitude. That is the best we can think of to overcome the problems while we are getting a really good way of doing it.

Mr. Stubbs, Plessey Co.

May I ask Mr. Russell why the tests were being done at 370°C?

Mr. Russell

I do not think we ought to enter into any discussion with regard to any particular temperature. They (Goodyear Aviation) have obviously got some special project in mind.

Mr. Stubbs

This is not just the normal requirement for aircraft at supersonic speeds?

Mr. Russell

Undoubtedly it will be.

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12   VOID FREE LAMINATES FOR RADOME CONSTRUCTION
      L. N. PHILLIPS, CHEMISTRY DEPARTMENT, R.A.E.

Mr. Mackay has shown how great improvement in erosion resistance can
be obtained when the standard Neoprene coating is applied over a void-free
laminate, as compared with the same Neoprene applied over a conventional
laminate.   In other words the quality of the base is of the utmost
importance and the radome designer should now think in terms of the best
quality, that is the void free quality, as the only quality for his base
material.

A great deal of work has been done just recently on the methods of
production of void-free laminates (both here at Farnborough and by a few
industrial concerns) and there is nothing difficult or impossible about
them.

With the use of surface-treated glass cloth and a polyester resin
which is not too viscous, then whether or not a void-free laminate is
obtained depends entirely on technique.   There are two basic principles
to be observed.   First of all, the air which is normally trapped during
the laying-up process must be swept from the laminate by a stream of resin.
Second the cure cycle must be controlled so that gas bubbles due to the
exotherm do not appear in the resin during or after gelation.   The conditions
after gelation are most important.   A perfect void-free lay up, when it is
rigid enough to handle can be ruined by putting in an oven at 70-80° because
the whole laminate becomes uniformly covered with bubbles.

There are four main techniques which can be used for making double
curvature void free skins as distinct from laboratory methods making only
flat sheet.

First there is the use of a vacuum bag which has very little resemb-
lance to the bag technique which is currently used in this country for
making radomes.   In the present method a rather low resin content is used.
After the lay up is finished a venting layer and a thick rubber bag is placed
over the assembly.   A vacuum of some 26-28 inches of mercury is applied and
then oven cure takes place at 100-110°C for 1 to 2 hours.   Experience shows
that the combination of deficiency of resin, opaque bag, high vacuum and
rapid hot cure is conducive to the formation of a large number of voids in
a laminate.

To achieve a void free lay up an excess rather than a deficiency of
resin must be used, the excess being used to squeeze out the bubbles.   This
operation requires a transparent bag so that the bubbles can be seen and
removed by manual pressure.   No venting layer is needed between the laminate
and the bag so the bag must part directly from the resin.   The initial stages
of gelation must be carried out without heating and under little vacuum: too
high a vacuum promotes vaporization and bubble formation as already described.

In the autoclave method, which is gaining favour in the U.S.A., the
initial vacuum process and technique remain as before, but when the voids
have been removed, the assembly is autoclaved under a further 30 lb/sq in.
pressure.

The pressure injection method has been introduced by the Bristol
Aeroplane Company.   Very briefly the method consists of positioning the dry
glass cloth between two accurately made moulds, and pumping in resin as a
suitable point so as to flush out the air from the laminate.   This is a very
ingenious system and is being demonstrated at the British Plastics Convention
on 9th June, 1955.

The vacuum injection method, developed some years ago by Dr. Muskat, is being used by English Electric, Luton for missile radomes. It uses two matched moulds as for the pressure method, but the resin is sucked up through the cloth from a trough at the bottom.

While on the subject of radome construction, mention should be made of low density cores. As aircraft operating temperatures increase, there is a danger that the chemically expanded plastic and Hycar cores will not be strong enough and consequently the mechanically expanded cores particularly the honeycomb type may be used increasingly for this type of work. There are two main defects to be overcome with honeycombs for radome construction. First is the lack of accuracy on core thickness. With the sawn honeycomb in particular the cut edges of the sheet have a somewhat springy fuzz of glass fibre, therefore, it is important that the apparatus which is set up for checking the thickness of the sheet should be loaded to give the same compressive stress which the core will experience during the bonding process. The second problem is in connection with glueing. It is difficult to get a good bond between a void free skin (prefabricated separately) and the honeycomb, by just brushing the skin with resin before assembly. One method which seems very good is to use a thin ply of glass cloth as a wet glue line, in conjunction with a dipped or roller coated deposit of resin on the honeycomb itself. In this way one can ensure that both surfaces have been wetted and that the two wet areas are brought into intimate contact.

One should not get the impression that all is known about void-free laminates, but it is clear that commercial production is a few weeks or months rather than a few years away.

In conjunction with A.I.D. work has just been started on a specification requiring an improved quality laminate.

A report on the present method of production of void-free laminates in radome construction will be published shortly.

12.1 Discussion

Mr. D. N. Hunter, D. Napier & Son Ltd

Could Mr. Phillips please tell me of what particular material the transparent vacuum bag is comprised?

Mr. Phillips

This particular material is a grade of plasticised Vinylite, the vinyl acetate-chloride copolymer made by Bakelite Ltd. I am glad you mentioned it because I would like to draw attention to the sealing of this bag. It is something that we have been developing with the firm of Plysu Products Ltd. Normally you make a bag such as that by an electronic welding process but we have been very worried about these little knobs where the lap joints meet. The importance of this bag is that we have attempted to make joints which are of a single thickness only and the method used is very interesting. First of all you make your normal lap joint just twice the thickness and then you take a much broader electrode, pass the whole seam back again through this electrode, and you squash the double down to the single thickness.

Mr. P. Alberricci, A. V. Roe and Co. Ltd.

Mr. Phillips, could you give us an idea of the maximum operating temperature of that type of bag and the life that you could expect of it?

Mr. Phillips

Maximum temperatures - a few degrees above room temperature for reasons which I have explained. The life is indefinite.

Mr. Alberricci

That immediately brings up the problem of what to do when you are trying to make a 14 ft radome. You could not use a room temperature activated resin because the whole thing takes at least 24 hours to lay-up and you have got to use a heat catalysed type of system.

Mr. Phillips

No Sir, you make an assumption which is quite unjustified. I would agree that you cannot use the normal sort of catalysis where you gel in an hour or so. You would use an ultra-violet system of cure. You would have your long lay-up time with no danger of gelation and then you would wheel the assembly beneath a battery of ultra-violet lamps and trigger it off in that way. I am quite sure that hot curing is the way to disaster.

Mr. Alberricci

Further to that point there was a lot of work done in America which stated that 70° was the critical temperature and below that point in actual fact you got void free laminates, but above this temperature you did get the pin holes, gassing of the monomer etc., that is present in a typical commercial laminate.

Mr. Phillips

There are three things here, time, temperature and vacuum. You cannot say categorically a particular temperature is or is not critical. With a very strong vacuum you can suck off enough monomer at room temperature to give you enough voids to make you worried. You cannot say categorically that $X^{\circ}C.$ is the limit and below it you would obtain void free laminates.

Mr. Alberricci

Is it true to say that most of the American radomes which are very good are not made with an ultra-violet catalysed system?

Mr. D. J. Hodgson, Microcell Ltd.

There is a rapid switchover in the U.S. to ultra-violet curing for this very reason and to avoid any undue heating of the radome during its manufacture.

Mr. Alberricci

What is the point at issue? Shrinkage due to temperature or boiling off of the monomer?

Mr. Phillips

Boiling off of the monomer.

Mr. Alberricci

A further approach to this would be to produce a non volatile monomer if you could get it. The point is it is no joke having just put in a 20 ft long oven to go back to one's Management and say we don't need it and we want to put in some new system. (Laughter)

Mr. Phillips

I take the point, (laughter) but I would say this, it is no fun either to go on to an aerodrome and see millions of pounds worth of machinery just lying there useless.

Mr. Alberricci

I am sure we are making at 70°C laminates which are void free, certainly as good as those exhibited on the table now.

Mr. Phillips

I should like to inspect them.

Mr. Hodgson, Microcell

I think it may be helpful if you give a definition of what you consider to be void free laminate. We have had this discussion before. What in fact at this juncture do you consider a void free laminate?

Mr. Phillips

That is a point. I do say if you get a strong light behind your laminate and if you cannot see, with a lens of magnifying power × 10, one pin hole per area of 4 sq/in. then I think that is pretty good. You should be able to repeat that on a very large structure.

Mr. Alberricci

How do you make the connection from the pressure pump on the vacuum system with this type of bag?

Dr. Megson

This is a question of requiring a lengthy answer. Would you please speak to Mr. Phillips separately on this point?

Mr. P. R. Green, The English Electric Co. (Luton)

With a solid homogeneous radome where the thickness is governed by electrical considerations we often find from the strength point of view that we have quite a lot in hand. Would you say that there is any advantage from the erosion point of view of having a good thick resin rich surface in which there is no glass at all?

Mr. Phillips

They go in this order - an ordinary commercial laminate is worse than the laminate which has a pre-gelled coat. You can put a thick layer of resin on top of a bad laminate and improve the performance slightly.

Mr. Goacher

Could you please say if there is any advantage or disadvantage in the

construction of void free laminates in using B stage cured resins?   There
are epoxy resins which can be B stage cured and I believe in the States
there are polyesters too, where the cloth is already impregnated and partly
gelled.

Mr. Phillips

Preimpregnation hinders but it does not prevent it.   There have been
tales of void-free laminates made by the pre-impregnated method but you are
in a dilemma.   If you have it too dry, i.e. nice and tacky, you have not
got enough resin to do the sweeping out of air without a lot of hard work,
so one is tempted to put a little bit more resin in, which makes the
sweeping out process easier and then perhaps the operative starts complaining
that it is a little bit too stiff.   It can just be done.

Dr. Megson

There may be a lot of details here that people would like to know
about and I would suggest that those of you who so desire should make
contact with Mr. Phillips and come to R.A.E. to see him.

13   PROTECTION OF MATERIALS FOR STRUCTURES OTHER THAN RADOMES
A. A. FYALL, CHEMISTRY DEPARTMENT, R.A.E.

Introduction

Although work on the R.A.E. rain erosion test rig is concerned mainly
with the testing and development of protective coatings for radomes, atten-
tion has been given to the examination of the erosion-resistant properties
of other materials used in aircraft construction, particularly those which
are incorporated in the design of specific projects.   In this paper special
application including aerial covers, fairings, transparencies and metals are
discussed.

Aerial covers

In addition to radar, there are also in the field of communication and
guidance, various radio appliances, many of which require aerial housings.
These will be subjected to rain erosion if any part is forward-facing, but
fortunately the problem of protecting them is not so acute as in the case of
the radome.   This does not mean that the erosion of these parts is any less
severe as the covers may be located in the leading edge of the wings or of
the fin, in the wing-tips or attached to the fuselage as a streamlined radio
mast.   The protective methods, however, can be made more effective because
the longer wavelengths used require the electrical properties of the housing
to be less stringent than in the case of a radome.   Consequently a thicker
coating of protective material can be tolerated.   Two materials in current
use for aerial covers have been tested in addition to the glass-fibre
laminate.

(a)   Birch plywood

Birch plywood, used at present as an aerial cover in the leading edge
of a tail fin, has been evaluated.   The usual method of keeping this type of
aerial panel watertight is to cover it with a layer of Madapollam cloth,
which is stretched on with several layers of taughtening dope.   The assembly
is finished with a top coat of pigmented cellulose.   Test pieces representing
such an assembly have been tested.   At 350 m.p.h. in 1 inch per hour rain-
fall, the fabric was exposed in 1 minute.   At 500 m.p.h. under similar
conditions, exposure for 1 minute resulted in the fabric being damaged.   Since

these conditions are likely to be experienced in service, alternative assemblies have been evaluated.

Two cold-setting plastic cements, one natural rubber with some neoprene, the other containing Neoprene in an ester base, were applied straight on to samples of bare wood. In both cases, the coating was stripped or worn away in a few minutes at 500 m.p.h. in 1 inch per hour rainfall. A coat of Neoprene 0.015 inch thick, to D.T.D.856A, applied on top of the Madapollam-cellulose system increased the protection to 45 minutes. As the failure in this case was due to lack of adhesion between the Neoprene and the top coat of pigmented cellulose, samples were prepared in which this top coat was omitted. Much better adhesion was obtained and the system lasted for 1 hour 45 minutes, the eventual failure being due to loss of adhesion between the Madapollam and the wood. A final test in which approximately 0.027 inch of Neoprene was applied directly on to the bare plywood, showed excellent adhesion and gave protection up to a maximum time of 4 hours 30 minutes. In considering these times, it must be emphasised that the plywood under the Neoprene usually fails in compression before the Neoprene layer is seriously eroded and thus the quality of the plywood surface, along with the interlaminar adhesion, would seem to be a governing factor in the life of this system.

(b)   Durestos

Durestos, which is an asbestos-filled phenolic resin, either low or high pressure moulded, can also be used as an aerial cover. Like most resin bonded materials, unprotected Durestos has very poor resistance to rain erosion. Early tests showed that Neoprene adheres very well to Durestos, provided the surface of the Durestos is suitably abraded and cleaned. Failure due to lack of adhesion should not normally be encountered. Due to the fibrous nature of Durestos, however, a good mould finish of the article is most necessary, as surface irregularities provide starting points for erosion. Such surface irregularities may initially provide a good key for adhesion of the Neoprene, but the eventual failure of the Neoprene will be primarily due to the failure of the Durestos underneath. On a well prepared sample, an erosion time of 2 hours 40 minutes has been obtained although figures as low as 10 minutes have been recorded. Tests made so far have been made with samples coated with up to 0.010 inch Neoprene but much thicker coatings could possibly be used to advantage.

Expanded materials

The need for frangible aerodynamic fairings for certain projects has led to the evaluation of expanded rubber specimens. Tests at 250 m.p.h. in 1 inch per hour rainfall showed that the cellular structure of the foam, although capable of withstanding large distributed loads, was quickly crushed under the high local impact of raindrops. Testing at 500 m.p.h. and 0.5 inch per hour rainfall was disastrous as shown in Fig. 26. A coating of Neoprene 0.027 inch thick was tested for 23 minutes in 1 inch per hour at 500 m.p.h. Although the Neoprene was only slightly damaged, the expanded rubber underneath was crushed to a fine powder and damaged to a depth of 0.1 inch. Samples protected by a 0.030 inch thick sheet of rubber, reinforced with nylon net fabric, gave similar protection for 7 minutes. This comparison should not be taken as conclusive as the quality of the mould finish of the expanded rubber affects the rate of erosion. It would seem that a coating of Neoprene 0.025 inch to 0.030 inch thick would afford some protection for 30 minutes at 500 m.p.h. in 1 inch per hour rainfall.

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Transparencies

Perspex

In view of the extensive use of perspex in forward-facing components such as canopies and observation panels, samples of Perspex were subjected to test in rain conditions.   At 500 m.p.h. in 1 inch per hour rainfall, the visibility through perspex is seriously reduced in 5 minutes.   In 10 minutes the Perspex has started to pit badly as shown in Fig.27.   If Perspex components are used for vision panels the angle of incidence to the line of flight must be arranged so as to avoid this damage.   As Perspex is a homogeneous substance and erodes readily, it was thought that it would be more suitable for measuring rates of weight loss than glass cloth laminates with their variations due to weave of cloth, resin concentrations etc.   A parameter for measuring rates of erosion, viz. weight-loss, would be most useful. Several tests were made and excellent agreement was obtained between the losses sustained by any two samples run simultaneously, but the correlation between duplicates was very poor.   This was due to the extent to which each pair was affected by moisture uptake.   As Perspex may take a month to reach full saturation, the obviation of such an error took so long as to make the scheme impractical.

Glass

Preliminary tests with glass have met with failure because of the loss of the specimens presumably due to the extreme notch sensitivity of glass and the high stresses involved in testing.

Metals

In the early experiments on the erosion resistance of glass cloth laminates it was noted that the aluminium end-caps holding the samples in position became pitted very badly.   Further observation showed that the anodic coating on the caps inhibited the initiation of erosion for some time.   Tests on solid aluminium specimens (D.T.D.423B) showed deep pitting and heavy erosion after 10 hours at 500 m.p.h. in 1 inch per hour rain as shown in Fig.28.   The onset of erosion may be delayed 2-3 hours by the application of a coating of 0.020 inch thick Neoprene.   Three other proprietary hard finishes have been tried on aluminium but all have either worn through or chipped off in a short time (e.g. in 10-40 minutes). Anodic coatings seem to delay the onset of erosion by several hours.   Fig.29 shows from left to right an ordinary aluminium sample, a similar sample coated with 0.020 inch thick Neoprene and one with an anodic coating.   It is doubtful whether the Neoprene affords any real protection since the coating will eventually fail in small areas providing nuclei for further impingement which may result in deep local pitting and the resultant damage may be worse in those areas than without protection.

General conclusions

Owing to the lack of basic knowledge of erosion mechanism, experience confirms that it is advisable to test all materials to assess their erosion resistance, rather than to assume the resistance to be similar to tested materials of corresponding physical properties.

13.1 Discussion

Mr. T. R. Barnett, London University (Royal Holloway College)

Mr. Fyall, what do these specimens of glass look like?   Could you describe them?   Were they similar to the Perspex ones?

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Mr. Fyall

Before treatment or after treatment?

Mr. Barnett

After treatment.

Mr. Fyall

As I have already said we only collected a few fragments, the rest are scattered somewhere over the R.A.E. We were trying to get the results on glass for this Symposium and consequently did not consider the design too carefully. You must realise that at the speeds at which the tests were made, a force of the order of 3,500 g was acting on the specimens and they simply disintegrated under these stresses.

Mr. Russell

May I add to this that the Americans at Cornell attempted to test glass in the conventional aerofoil section shape and they have recovered some of their specimens. They have got quite deep pits on the leading edge and not the roughening that we have observed in Perspex.

Mr. Barnett

Had plastic deformation occurred?

Mr. Russell

I would not care to say what the mechanism was.

14 CONFERENCE SUMMARY BY CHAIRMAN, DR. N. J. L. MEGSON
CHEMISTRY DEPARTMENT, R.A.E.

Miss Shilling, Gentlemen, we have come to the end of our time here and perhaps before we go it might be an idea if I tried to sum up what we have been doing today.

It must be obvious to you that we should not call together a meeting of this kind unless the problem that we were going to discuss was one of great importance. I hope it has been clear today that the problem of rain erosion is also one of extreme complexity. There are so many factors involved here: people like the aerodynamicists have to have a particular design for their structures, the electrical people need various electrical characteristics that must be conformed to, and the engineers require certain strength characteristics. In many cases when you have that kind of position it is possible to reach some sort of compromise, but here the matter is more difficult, because the design, electrical and strength requirements may be incompatible with each other from the materials point of view. As a result, the provision of suitable materials becomes a hard task.

Quite apart from the question of materials, the actual techniques for examining erosion phenomena involve considerable difficulties. We have heard Mr. Bigg, Dr. Strain, Mr. Jenkins and Mr. Stubbs describe their particular pieces of experimental work, and Mr. Russell has well summarized U.S. investigations. Furthermore, Professor Tolansky has indicated another technique, using optical methods for examining surfaces, which may

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well prove of great value from the fundamental standpoint.   For devising appropriate experimental methods, a knowledge of meteorological conditions likely to be encountered is of the greatest importance: Mr. Murgatroyd has provided an excellent background in his paper.

The method using a spinning arm, which you have seen in operation today, is likely to be extended to higher speeds, but here again serious difficulties are likely to be met.   The material of construction and the design of an arm to provide speeds of say Mach 2 raise problems quite apart from those caused by noise and high power requirements.   Nevertheless it is hoped to tackle these higher speeds in due course.

Mr. Mann has given a clear review of the exacting electrical require- ments necessary in radomes, while Mr. Mackay has emphasized the need for care in applying the protective coatings so far developed.   Much controversy arose, as was to be expected, over Mr. Phillips' contention that void free laminates are essential if erosion is to be reduced to a minimum.   It is realised that the views of both Mr. Mackay and Mr. Phillips are likely, if put into practice, to cause difficulties in production, but I am convinced that these difficulties have got to be overcome.   We cannot tolerate high- speed aircraft lying idle, for want of radomes which undoubtedly can be made satisfactorily at the cost of additional trouble during manufacture.

Finally, Mr. Fyall has shown that erosion problems can arise in cases other than radomes, and has indicated that work must therefore continue on a wide variety of materials.

Before we leave, I am sure you would wish me to express our appreciation to those who have contributed papers today, and to those who have taken part in the discussions.   We owe a special debt to those responsible for organizing this meeting, and I would particularly thank Dr. Strain and Mr. Fyall who have shouldered the major part of the work. In conclusion, I thank you all for your attendance, and hope that you have found our proceedings interesting and stimulating.

Attached

Drgs. Nos. Chem. 2214, 2218 - 2223   Negs. Nos. 121,947 - 121,958
Detachable abstract cards

Advance distribution

CS(A)	ADARD(Res)	Director, RAE
Chief Scientist	ADMXRD(M)	DDRAE(A)
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PDLRD	ADRDL(2)	" GW "
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DGAP	on Plastics (Dr.W.W.Wright)	
DMXRD	Chem/RAE) 30	
ADSR(Records)	Sec. Joint R & D Committee	
AD Mat RD(Air)	on Rubber (Mr.W.J.Bloomfield	
ADARD(T)	Mat RD9) 20	
ADARD(I)		

APPENDIX I

The following representatives attended the Symposium. It is hoped that this list is complete and correct. Some representatives were unable to attend because of transport difficulties arising out of the railway strike. The decision to hold the Symposium in spite of the emergency has been justified by the large number who were able to arrange alternative means of transport.

Admiralty	D.A.E.R.	Dr. O. V. Richards
	Naval Aircraft Materials Lab.	E. J. Hammersley
		R. C. Clark
Air Registration Board		L. A. Hancox
Air Ministry		R. F. Jones
		Sqd/Ldr. C. Jordan
Aeronautical Inspection Department		
	(Chessington)	R. H. Billingsley
	(Harefield)	Dr. W. G. Shilling, M.C.
		J. C. Thomas
Armstrong Whitworth Ltd.		P. L. Britton
		D. A. Woodley
Ashdown Ltd.		A. W. Schofield
		C. C. Smith
B. B. Chemical Co. Ltd.		A. Bramley
		I. C. Hatton
		W. H. Swire
Boulton Paul Aircraft Ltd.		A. J. H. Lines
Bristol Aeroplane Co.		C. Bailey
		W. A. Baker
		N. Evans
		H. Hill
		R. G. T. Munday
		J. Rees
		M. J. Tayler
Chelton (Electrostatics) Ltd		W. T. Sanderson
		H. R. Smith
De Havilland Aircraft Co.	(Christchurch)	G. B. Evans
		R. C. Gilbert
	(Hatfield)	J. K. Crowe
De Havilland Propellers Ltd.	(Hatfield)	Dr. G. H. Hough
Elliott Bros. (London) Ltd.		D. E. Cronin
		J. A. Jones
The English Electric Co.	(Luton)	S. C. Dunn
		P. R. Green
	(Warton Aerodrome)	G. Hinnells

APPENDIX I (CONTD.)

Expanded Rubber Co.	A. Cooper
The Fairey Aviation Co. Ltd. (Hayes)	J. B. Cameron
Ferranti Ltd. (Manchester) (Edinburgh)	W. Cross G. Weeden
Folland Aircraft Ltd.	R. O. Gates R. K. Page
General Electric Co. Ltd (Stanmore)	R. M. Curr G. Gordon J. C. Saunderson
Gloster Aircraft Co.	R. G. Lander J. S. Louch
Goodyear Tyre and Rubber Co.(G.B.) Ltd.	J. W. Denson G. Marlow
Handley Page Ltd. (Cricklewood)	R. L. Hayes
Hawker Aircraft Ltd.	G. T. Beauchamp E. A. Tagg
I.C.I.	G. L. Knott E. J. Robins
London University (Royal Holloway College)	T. R. Barnett V. R. Howes Prof. S. Tolansky
Marston Excelsior Ltd.	R. J. Wareing
Microcell Ltd.	Dr. G. Ader A. Craig D. J. Hodgson
F. G. Miles Ltd. (Shoreham)	D. S. Bancroft
Ministry of Supply (Headquarters).	H. S. C. Bassett SERV. RD 1 W. J. Bloomfield Mat RD 9 Dr. M. G. Church Mat RD 7 R. Graham DARD W. Hardy AD Mat RD W/Cdr. W. T. Harrington O.B.E. SERV RD 1 F. W. Johnson AD/RDL 1 F. S. Nash RDT 1 L. Pearson APS (Mat) 2 J. H. Phillips ADGW (G & C) F. Radcliffe GW(E) P. H. Watson ADARD(T) C. F. A. Wagstaffe ADLRD(A)1 C. S. Wills RDN 2
N.G.T.E.(Pyestock)	D. L. Martlew

APPENDIX I (CONTD.)

Ministry of Supply (R.A.E.)	A. S. Atkinson Chem.
	F. J. Bigg ME
	H. Brooks Metal.
	F. G. J. Brown Structures
	A. A. Fyall Chem.
	S/L R. E.,W. Harland GW
	P. B. Hovell Structures.
	D. C. Jenkins ME
	D. Johnson Aero (part-time)
	Dr. F. E. Jones DDRAE(E) (part-time)
	J. Mackay Chem.
	Dr. N. J. L. Megson Chem.(Chairman)
	R. J. Murgatroyd Met. Res. Flight
	Dr. A. W. Lines GW
	L. N. Phillips Chem.
	D. G. A. Rendel ME
	W/Cdr. D. W. Rowson GW
	E. W. Russell Chem.
	V. Russell GW
	Miss B. Shilling ME
	Dr. R. N. C. Strain Chem.
	H. C. B. Thomas ME
	S/L K. F. Venn GW
	M. G. B. Weedon GW
R.R.E. Defford	G. B. Brushfield
R.R.E. (Malvern)	L. H. Mann
	A. M. Munro
R.T.O. (Armstrong Whitworth Ltd)	G. W. Suggett
D. Napier & Son Ltd.	R. D. S. Crick
	D. N. Hunter
	J. A. Rogers
	Dr. R. A. Roper
Oxford University	Prof. G. F. J. Temple
The Plessey Co. Ltd. (Towcester)	F. Marson
	N. C. Moore
	H. G. Stubbs
R.E. Components Ltd.	J. R. Schofield
A.V. Roe & Co. Ltd.	P. Alberricci
	W. G. Jones
Short Bros. & Harland Ltd.	K. L. C. Legg
	A. J. Steven
Thermo-Plastics Ltd.	R. Bennett
	M. Lewin

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APPENDIX I (CONTD.)

Vickers Armstrongs Ltd (Weybridge)	W. Astley
	E. M. Goacher
	A. G. Hill
	W. Jenkins
	G. A. D. Shaw
	E. Smith
(Winchester)	K. W. Hetzel
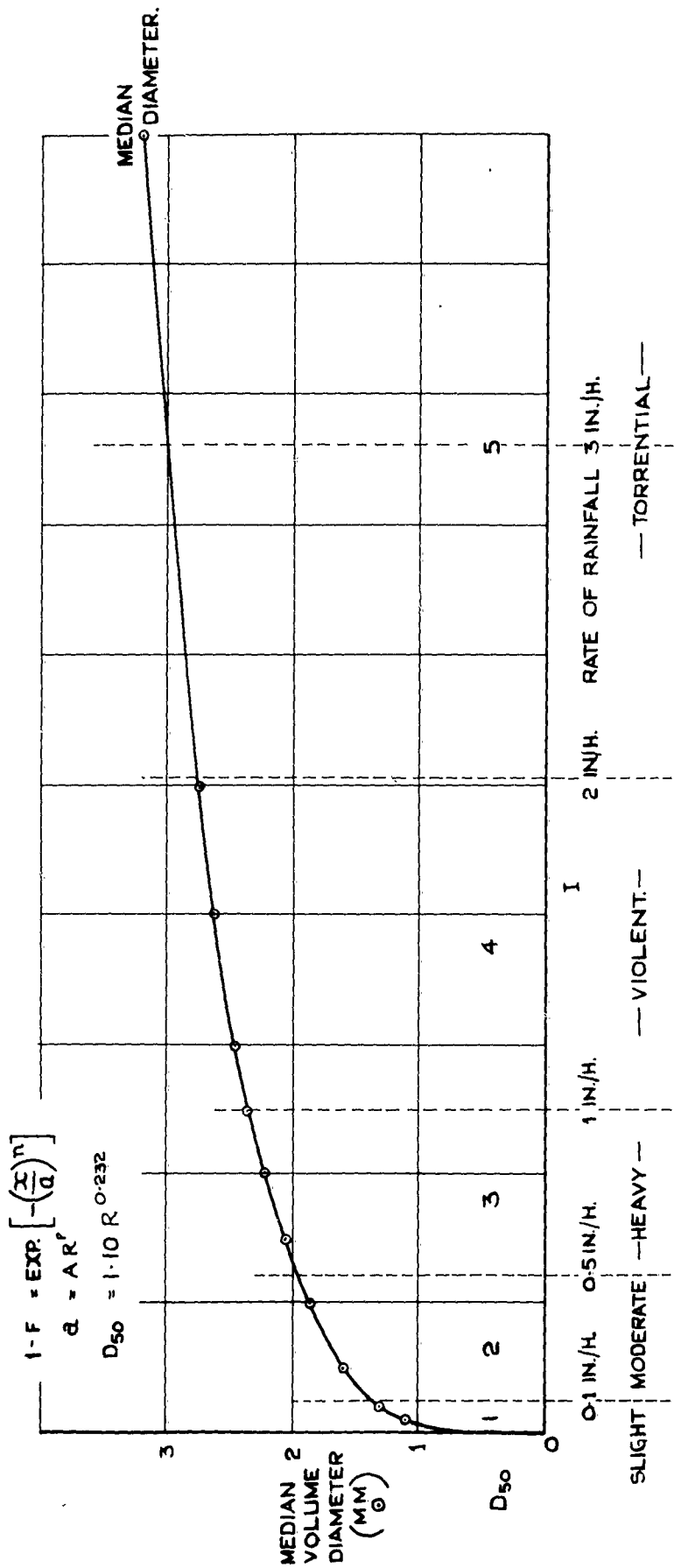
FIG. I VARIATION OF MEDIAN VOLUME DIAMETER OF RAINDROPS
WITH RATE OF RAINFALL.
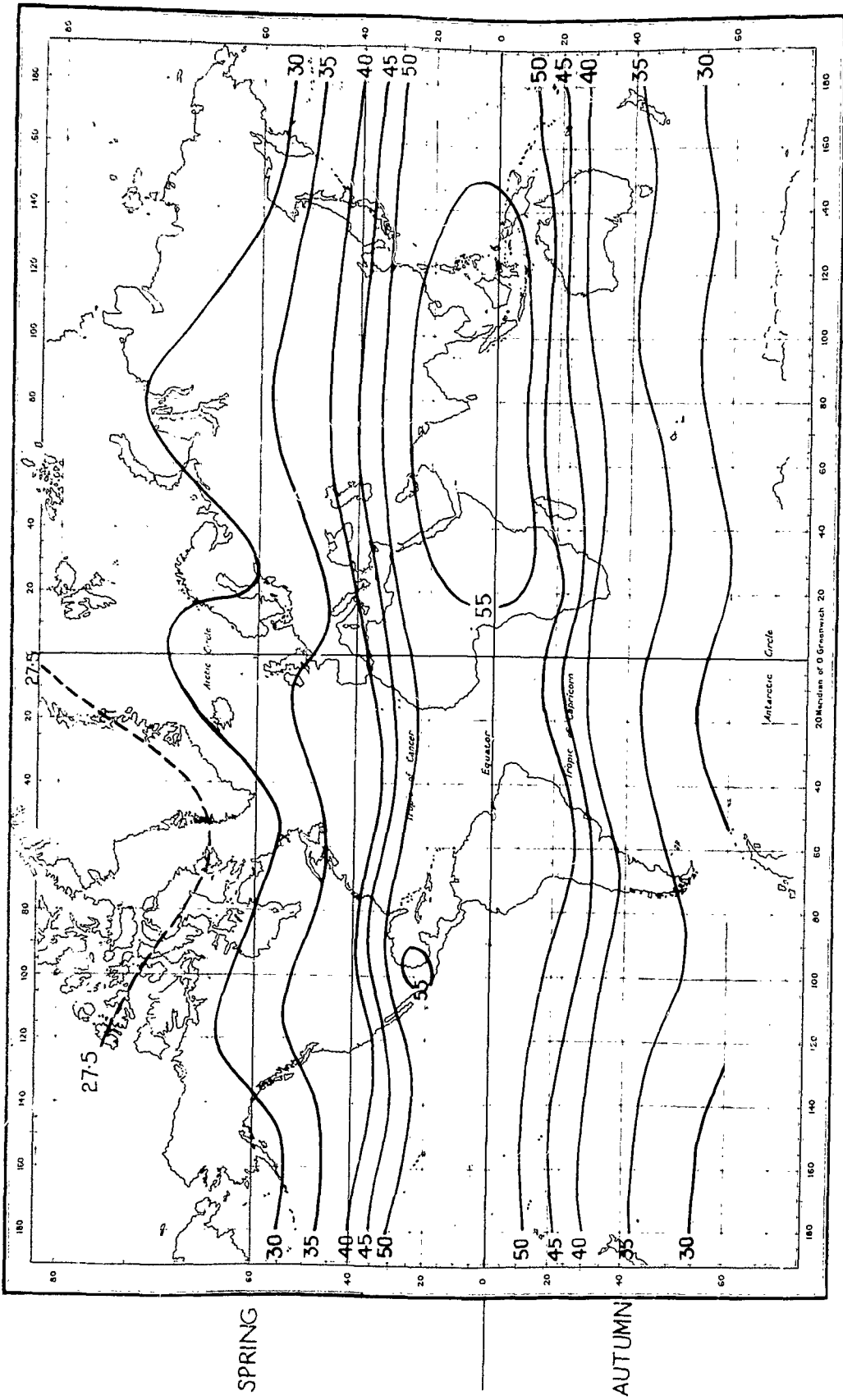
FIG.2. CONTOURS OF MEAN HEIGHT OF TROPOPAUSE   Thousands of feet

RAE 121947 55
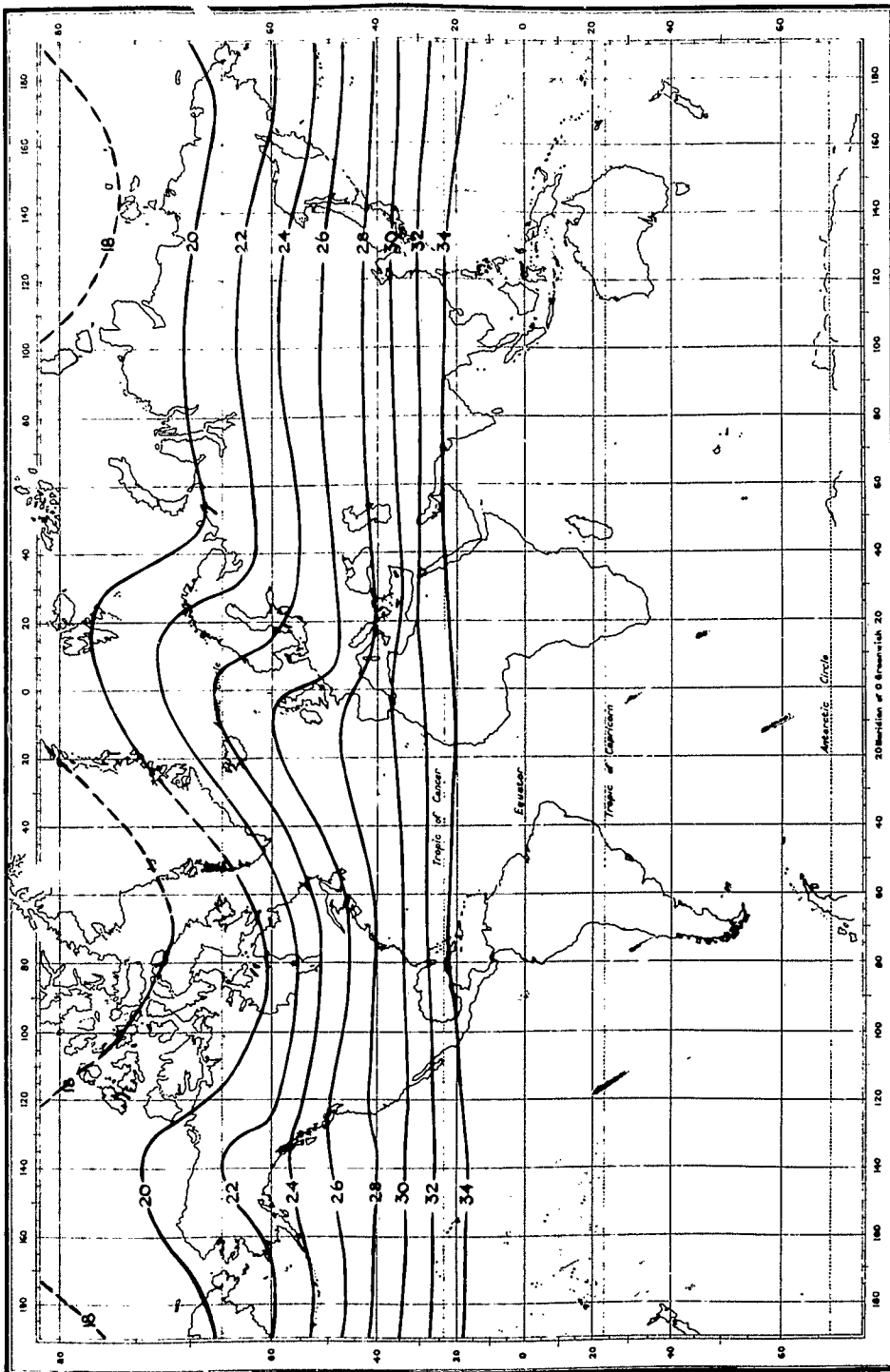
FIG.3. CONTOURS OF MEAN HEIGHT OF ISOTHERMAL SURFACE OF –40°C.
(Thousands of feet above sea level): April.
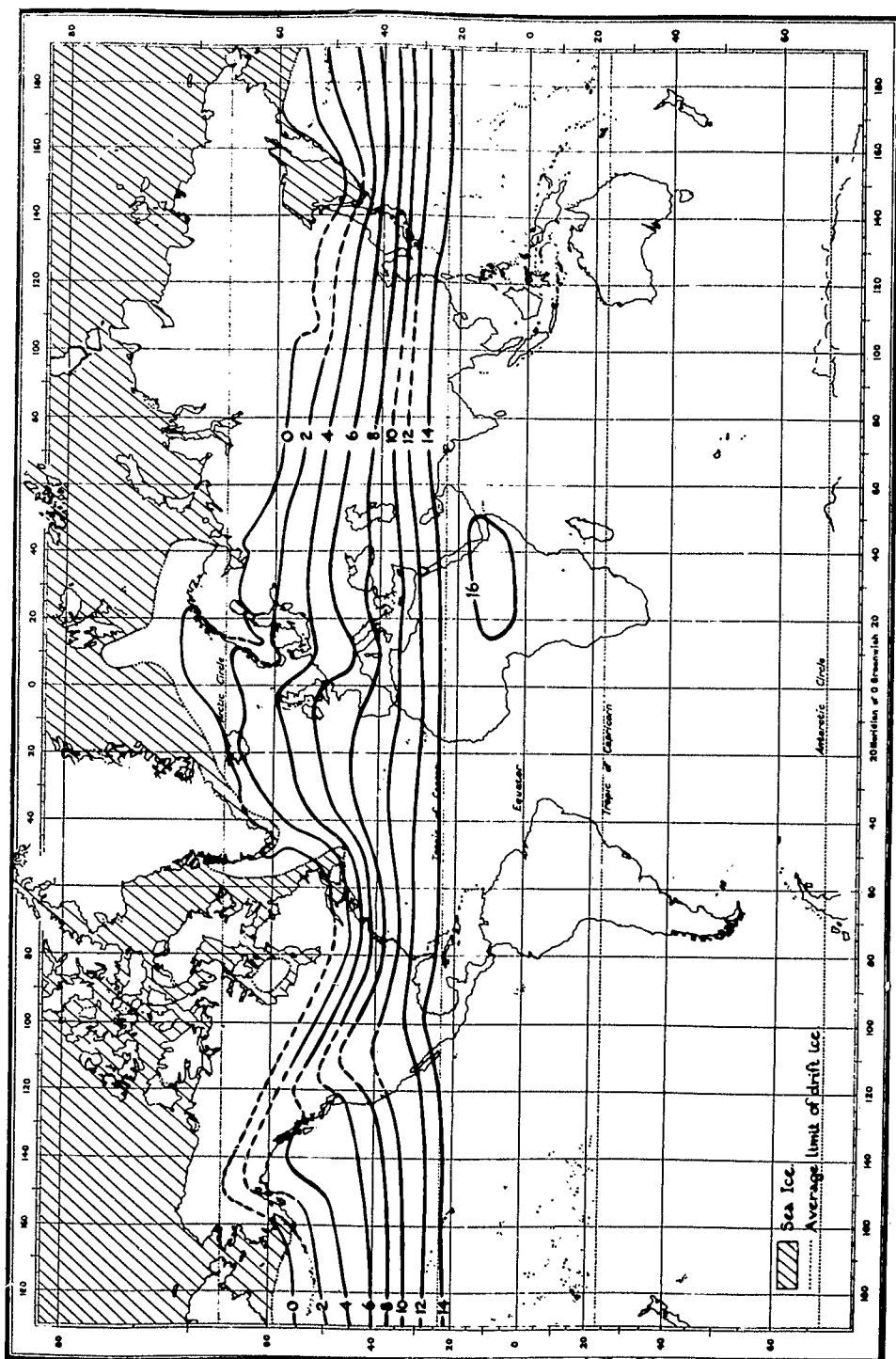
FIG.4   CONTOURS OF MEAN HEIGHT OF ISOTHERMAL SURFACE OF 0°C
Thousands of feet above sea level: April
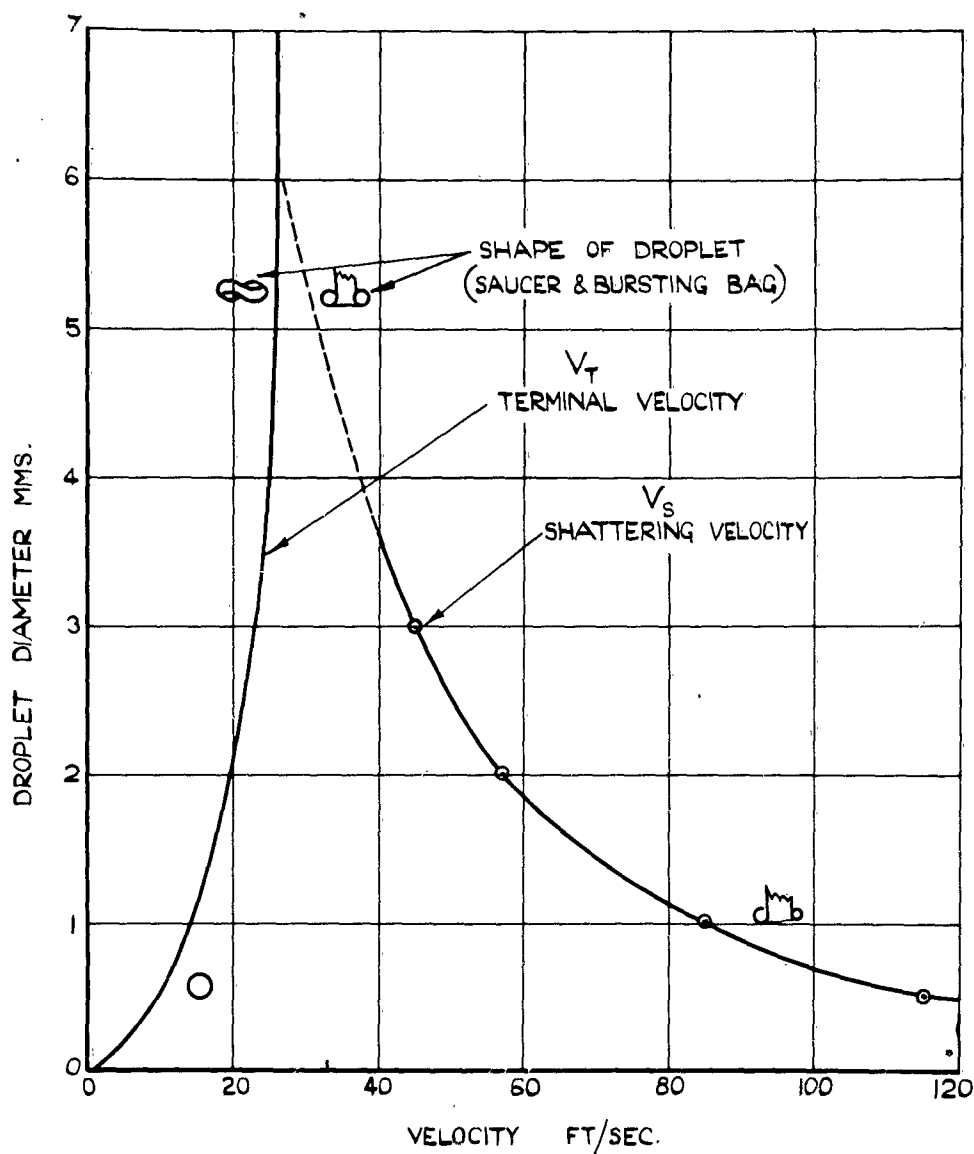
FIG. 5. TERMINAL AND SHATTERING VELOCITIES
OF WATER DROPS.

FIG. 6.

FIG. 6. DIAGRAM OF R.A.E. WHIRLING ARM & GLASS - POLYESTER TEST PIECES.
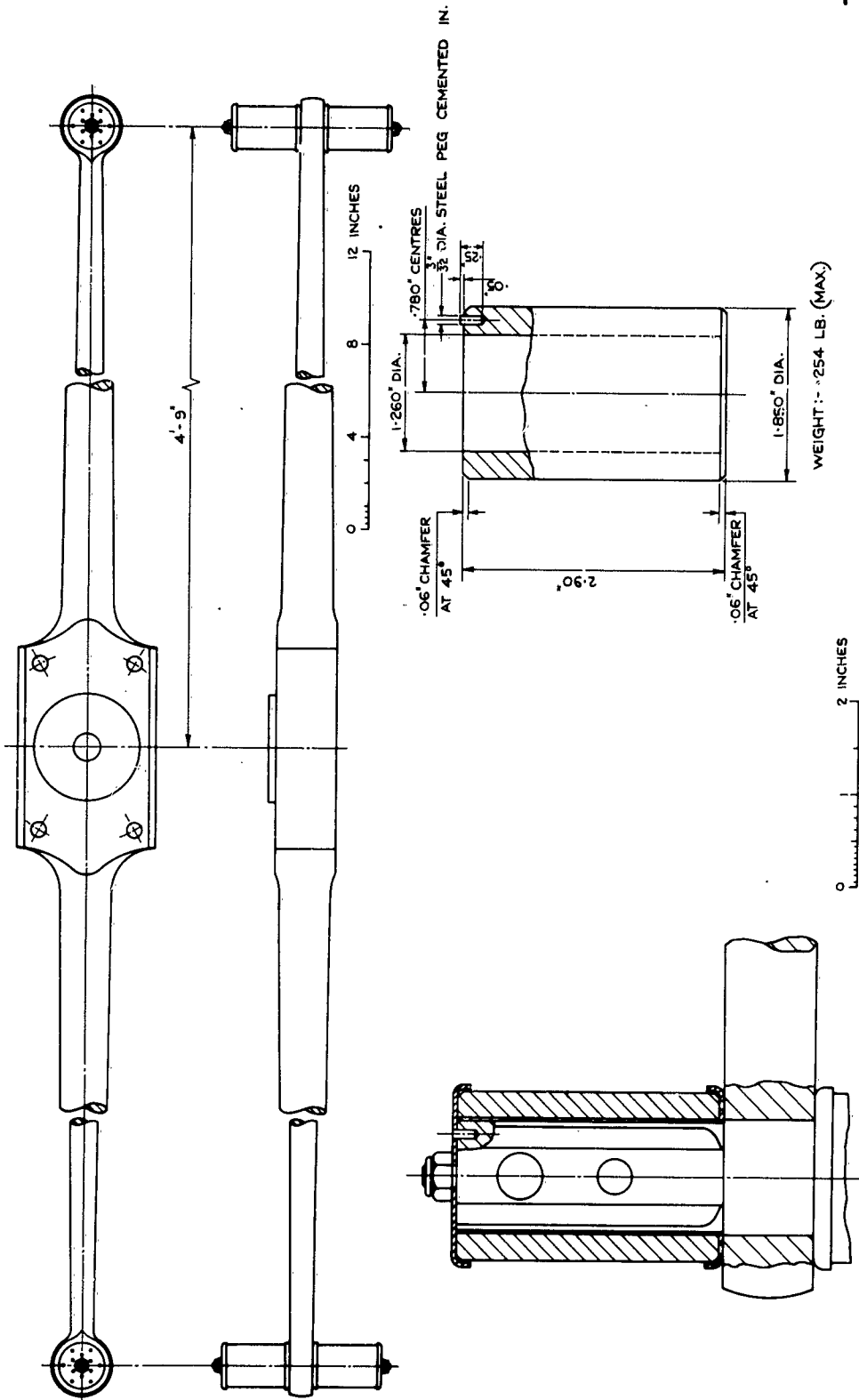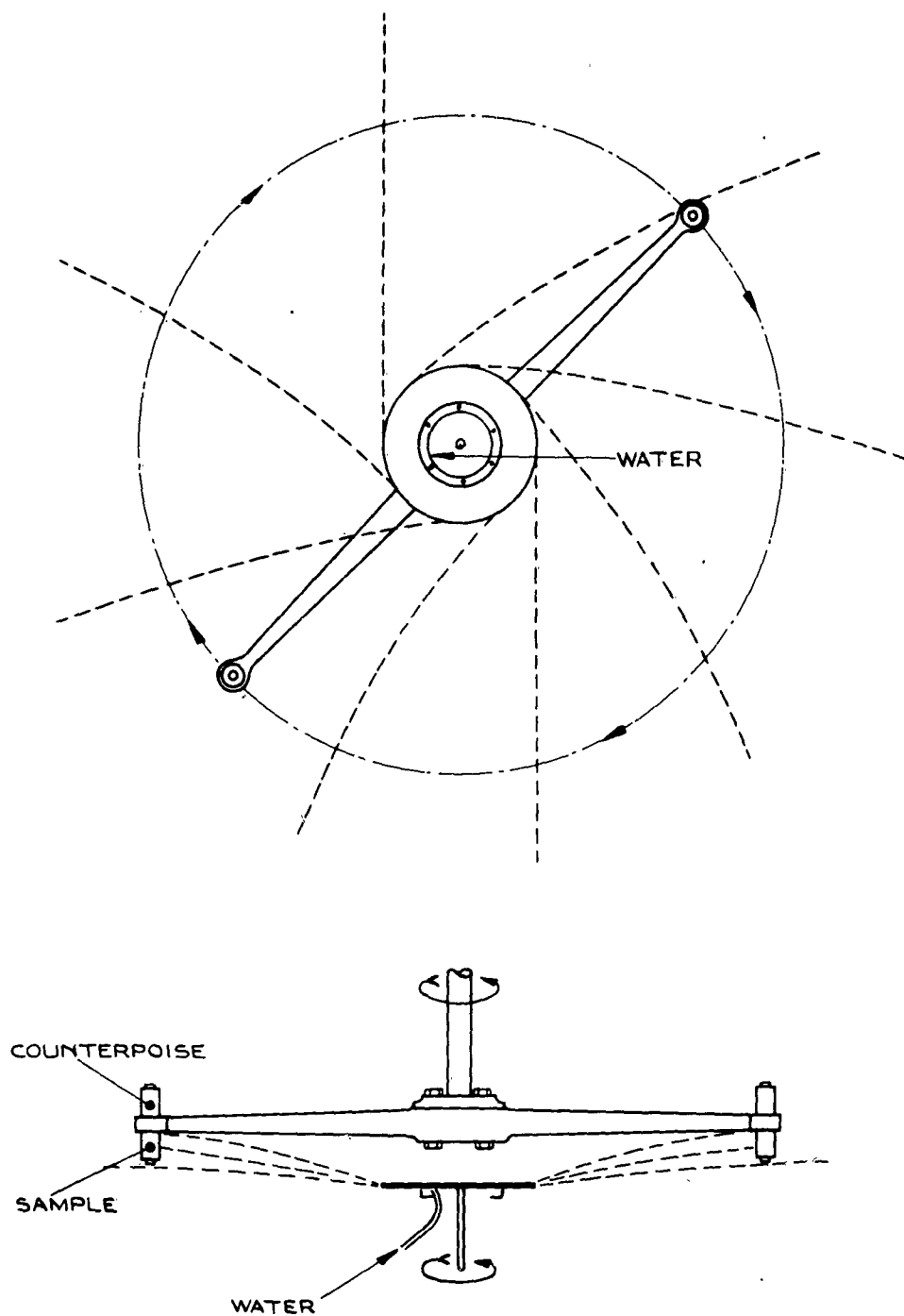
FIG. 7. METHOD OF SIMULATION OF RAIN FOR THE R.A.E. WHIRLING ARM.
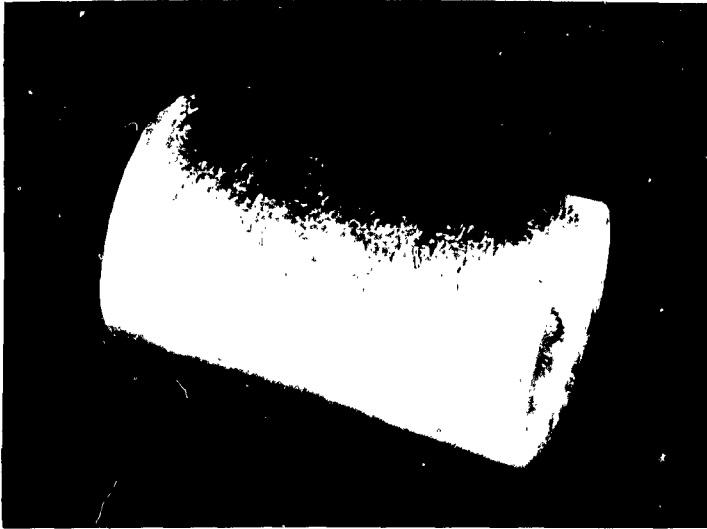
FIG.8. EROSION OF GOOD QUALITY
GLASS FABRIC / POLYESTER LAMINATE
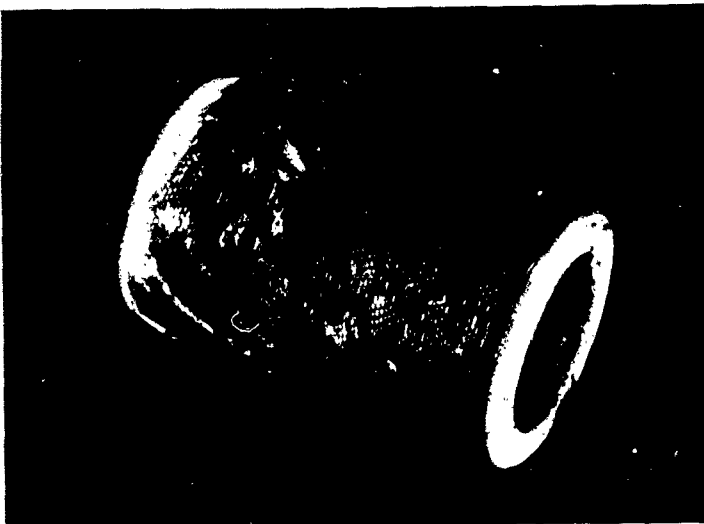
FIG.9. EROSION OF POOR QUALITY
GLASS FABRIC / POLYESTER LAMINATE

RAE 121950 55
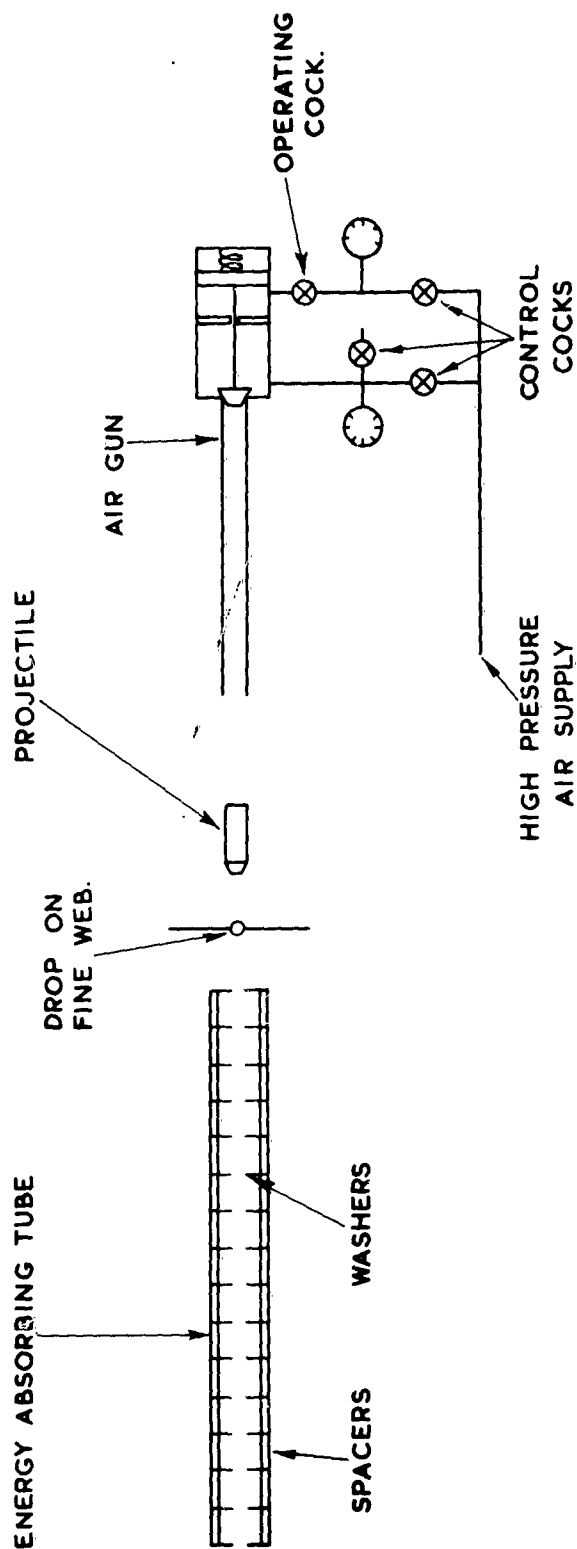
FIG. 10. DIAGRAMMATIC ARRANGEMENT OF GUN APPARATUS.
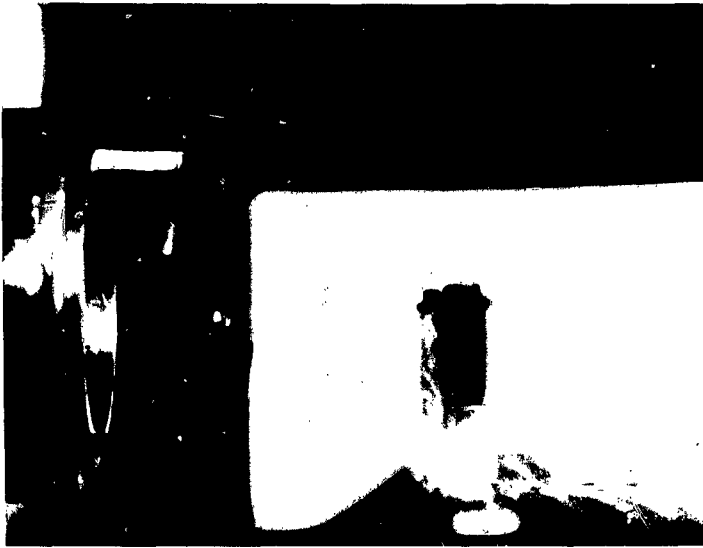
FIG.II. WATER DROP (2.5 mm. dia.)
SUSPENDED FROM A SYNTHETIC WEB
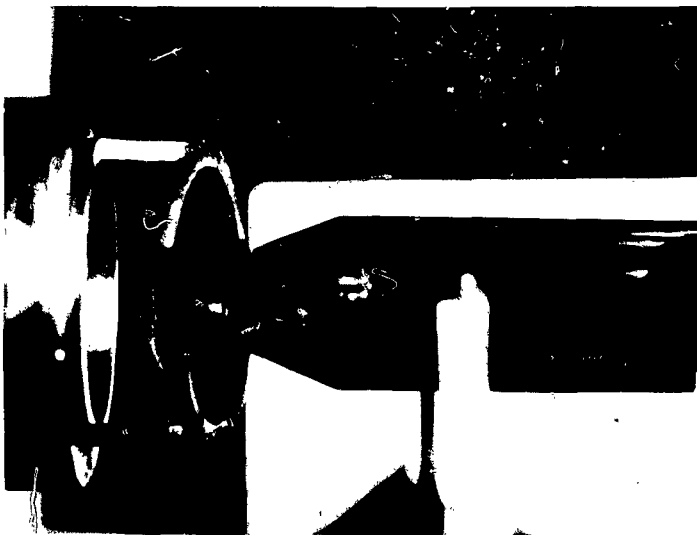
FIG.12. A PROJECTILE ABOUT TO STRIKE
A WATER DROP AT 770 ft./sec.
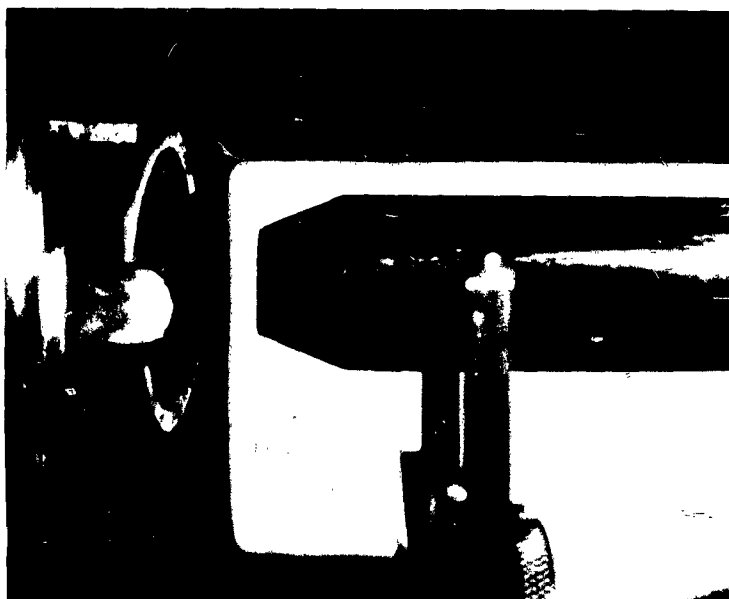
FIG.13. SHATTERING OF A WATER DROP DUE TO
ITS PROXIMITY TO THE GUN MUZZLE
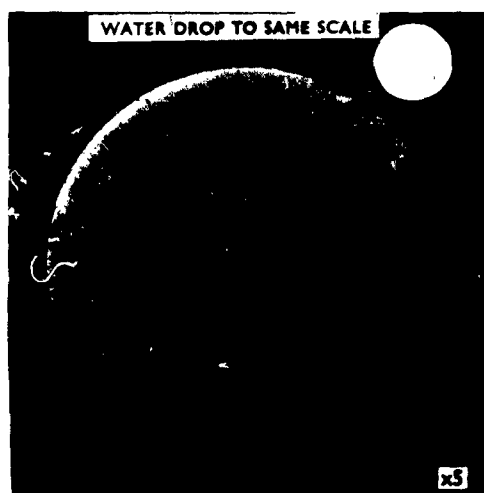
FIG.14a. SPHERICAL DROP
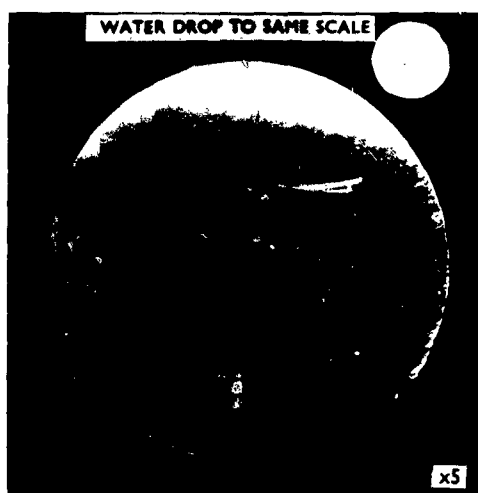
FIG.14b. SHATTERED DROP

FIG.14. MARKS MADE ON THICK ALUMINIUM
AFTER IMPACT WITH WATER DROPS
(2.5 mm. dia.) AT 800 ft./sec.

WATER DROP TO SAME SCALE

×5

FIG.15a

×15

FIG.15b

×95
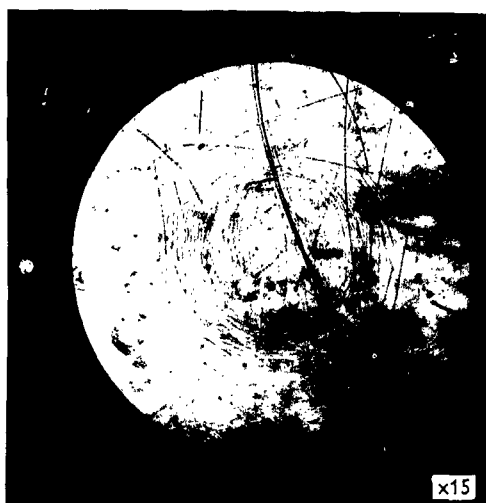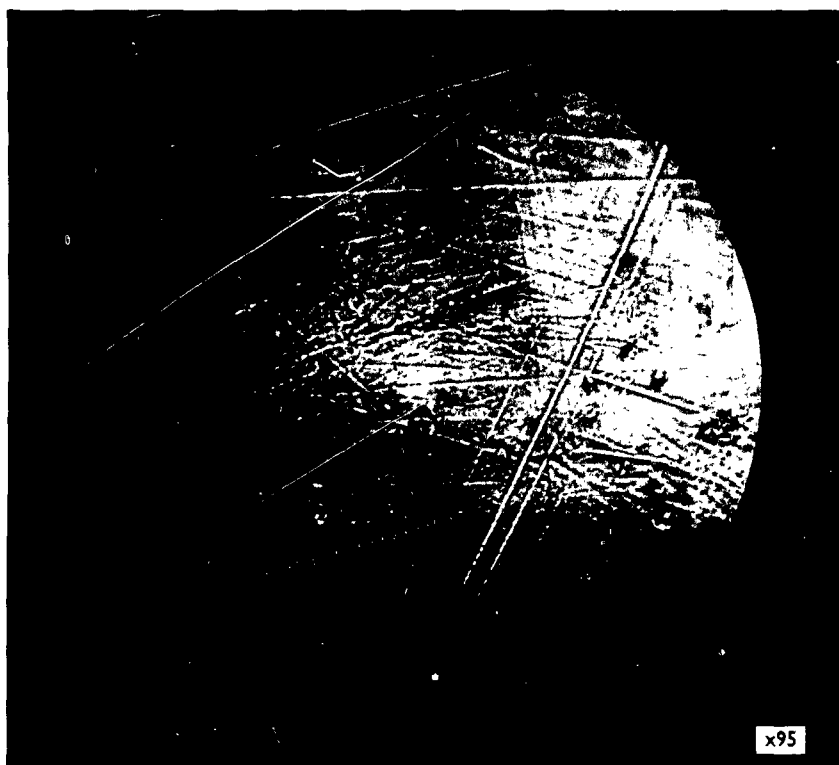
FIG.15c

FIG.15. MARK MADE ON PERSPEX AFTER IMPACT
WITH A WATER DROP 2.5 mm. dia. AT 800 ft./sec.

FIG.16a.   800 ft./sec.
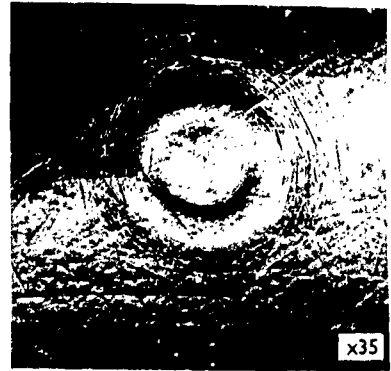
FIG.16b.   680 ft./sec.

FIG.16c.   550 ft./sec.

FIG.16.   MICROGRAPH OF MARK PRODUCED ON
PERSPEX AFTER IMPACT WITH A WATER
DROP (2.5 mm. dia.) AT VARIOUS SPEEDS
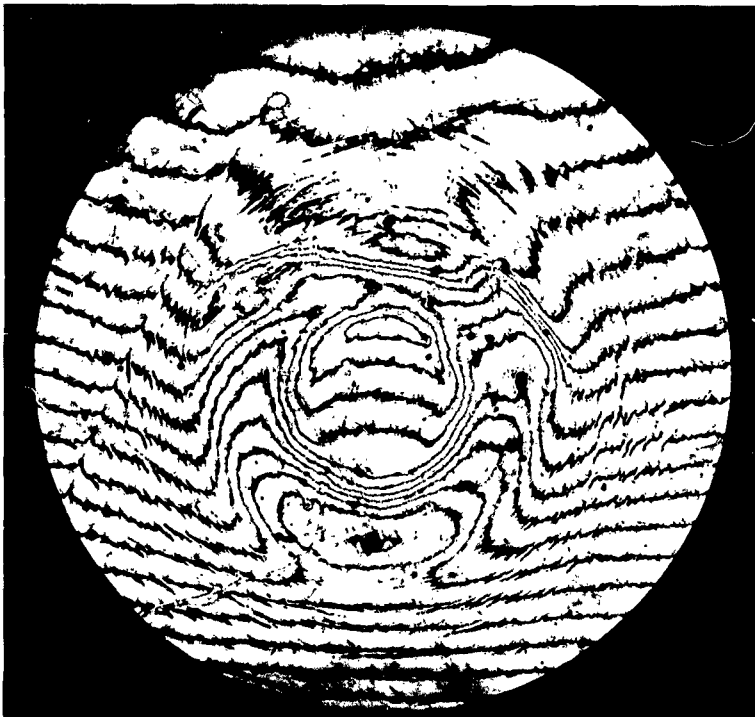
FIG.17.   MULTIPLE BEAM FIZEAU FRINGE PATTERN OF THE
MARK PRODUCED ON PERSPEX AFTER IMPACT
WITH A WATER DROP 2.5 mm. dia. AT 800 ft./sec.
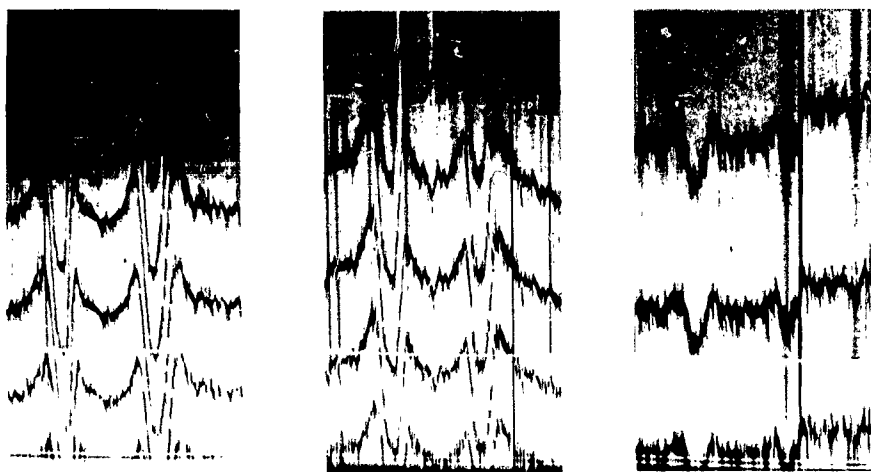
FIG.18. FRINGES OF EQUAL CHROMATIC ORDER FOR A DIAMETRICAL
SECTION OF PERSPEX AFTER IMPACT WITH A WATER DROP
(2.5 mm. dia.) AT VARIOUS SPEEDS
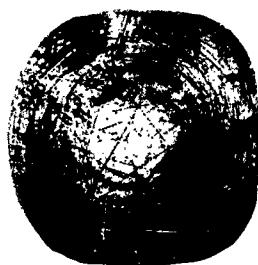
FIG.19. CRAZED REGION IN PERSPEX AFTER IMPACT WITH
A WATER DROP (2.5 mm. dia.) AT 680 ft./sec.
PHASE CONTRAST PHOTOGRAPH)

FIG.20. THE PLESSEY CAVITATION EROSION APPARATUS
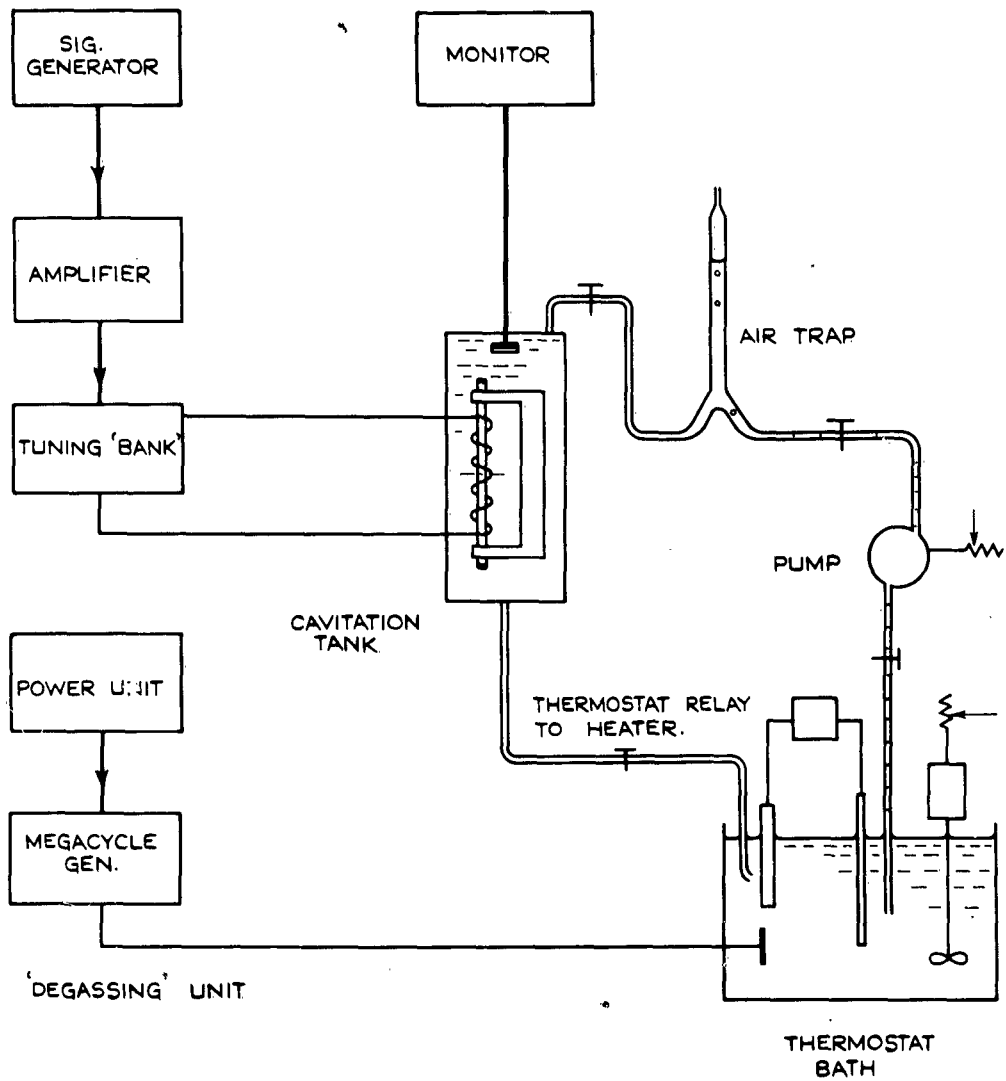
FIG. 21. DIAGRAMMATIC REPRESENTATION OF PLESSEY CAVITATION EROSION APPARATUS.

FIG. 22.
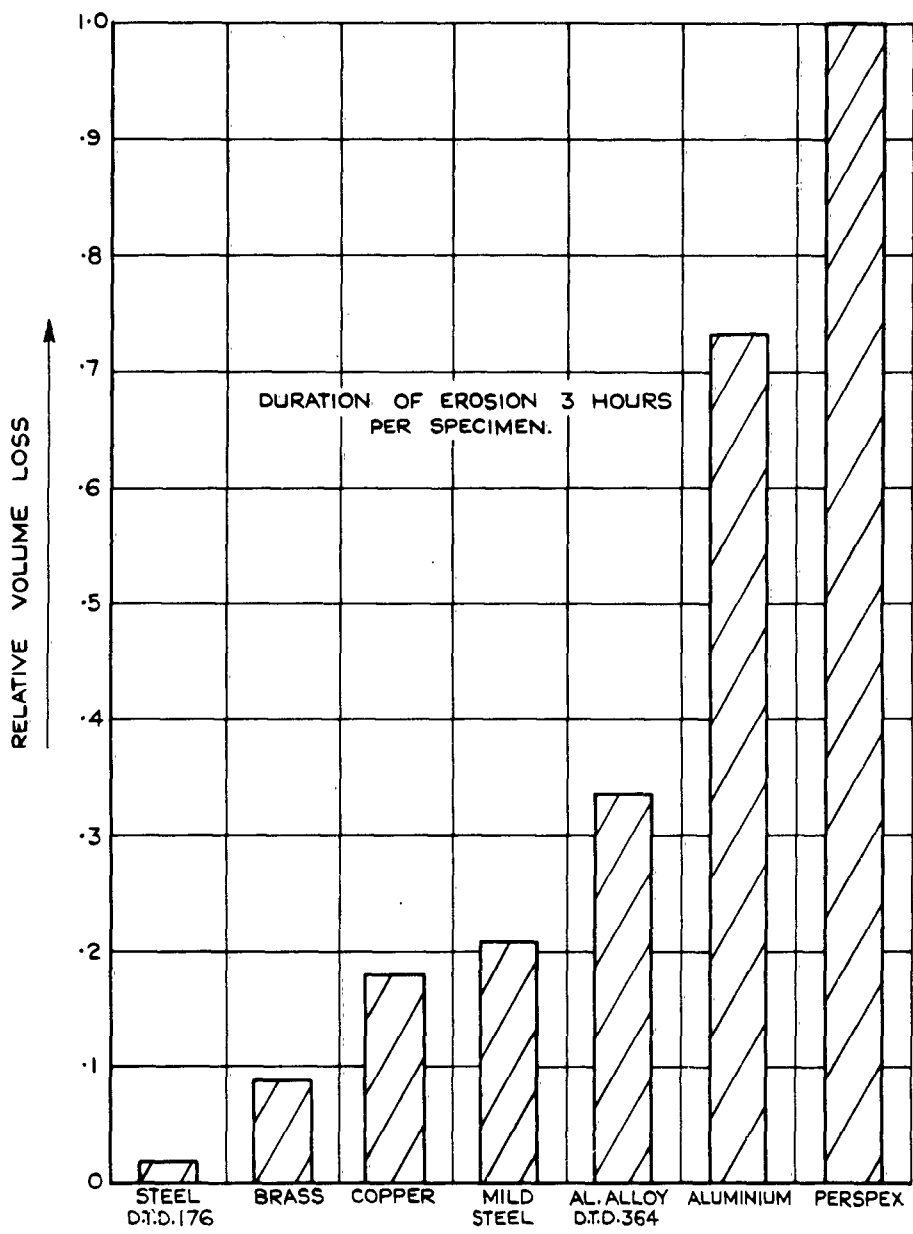
FIG.22. RELATIVE VOLUME LOSS FOR VARIOUS MATERIALS (PLESSEY APPARATUS)
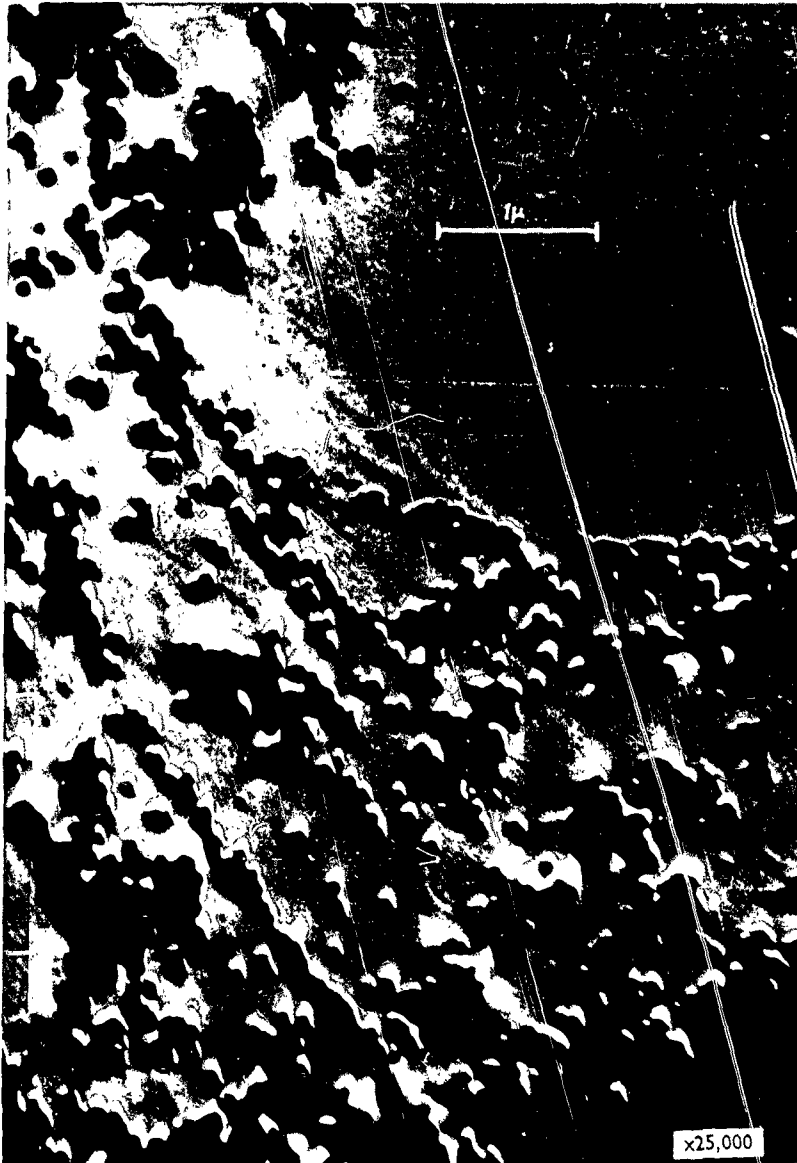
FIG.23. ELECTRON MICROGRAPH OF CAVITATION ERODED GLASS
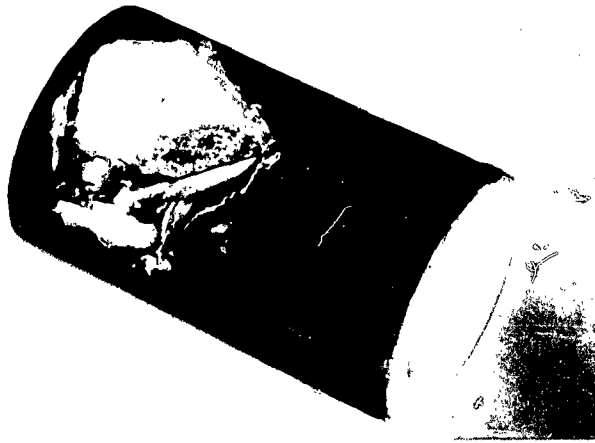
FIG.24. PREMATURE FAILURE DUE TO LACK OF ADHESION
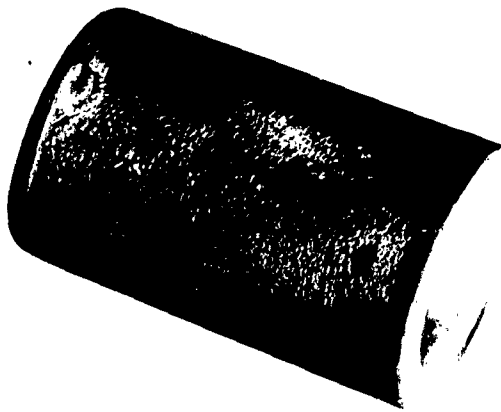OF POOR QUALITY NEOPRENE-COATED LAMINATE
15 min: 500 m.p.h: 1 in./h RAIN

FIG.25. UNIFORM EROSION OF GOOD QUALITY
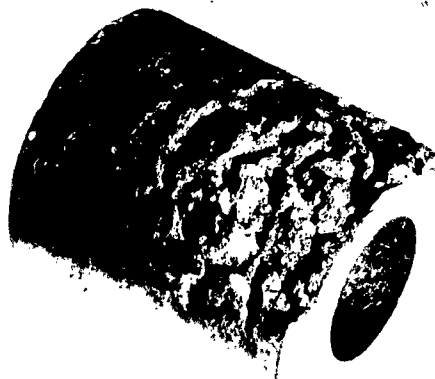NEOPRENE-COATED LAMINATE
200 min: 500 m.p.h: 1 in./h RAIN

FIG.26. EROSION OF EXPANDED RUBBER
1 min: 500 m.p.h: 0.5 in./h RAIN

FIG.27. EROSION OF PERSPEX
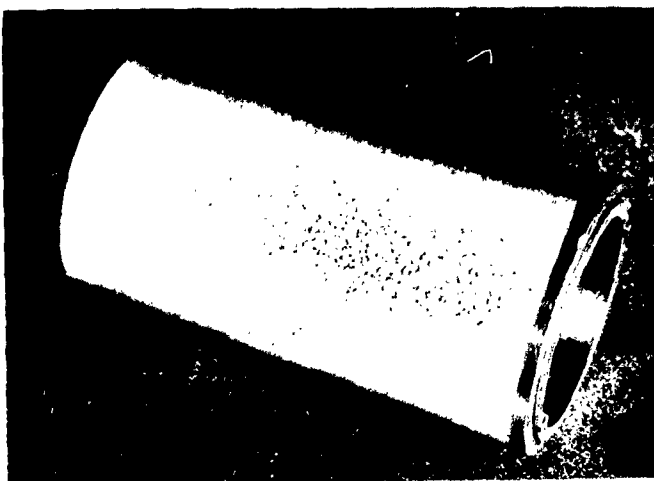10 min: 500 m.p.h:
1 in./h RAIN

FIG.28. EROSION OF ALUMINIUM ALLOY (D.T.D.4233)

FIG.29. EROSION OF ALUMINIUM ALLOY
(500 m.p.h: 1 in./h RAIN)
a. UNPROTECTED POLISHED ALLOY AFTER 10 h
b. NEOPRENE COATED ALLOY AFTER 215 m
c. UNPROTECTED ANODISED ALLOY AFTER 10 h

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